Alternatives to sandbags for temporary flood protection

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Summary

This study deals with new, innovative methods that can replace sandbags as temporary flood protection measures. It is essentially a review of available published literature and commercial brochures. Proposed new techniques and methods were critically evaluated based on common professional practice and gathered experiences in flood fighting. The following aspects of each alternative were assessed:

- stability with respect to sliding, overturning, seepage and soil loading;
- constructability, including simplicity of design, rate of construction, equipment and manpower requirements, terrain adaptability, etc.;
- costs, including capital acquisition, storage and maintenance;
- previous experiences in flood protection; and
- additional issues (versatility in use and similar).

The following systems were chosen to be recommended for further experimental and practical testing.

Inflatable (water or air-filled) tubular geomembranes, have the widest possible area of application: in urban and rural areas, almost without restrictions regarding the relief and underlying soil, with the fastest installation time and least requirements regarding the equipment. They are very good as closure structures for still and slowly flowing water, up to 1.5 m high.

Cellular (gabion-like) structures are suitable for harsh conditions in rural areas: for stream diversion and confinement, for currents which carry sharp boulders and dangerous floating debris, for extreme cold, etc. The retained water is usually about 1 m, but may be up to 3 m high.

Post-and-lagging systems are the best (and the most expensive) closing structures for vital infrastructural objects in urban conditions, particularly for high levels of floodwater – up to 4 metres, with proper support and provided that the foundation structure is solid and stable.

Jersey highway barriers may be used for levee raising in urban conditions with good accessibility, and for lower retained heads of floodwater - up to 0.5 metres.

None of these systems can be considered as an ideal solution, but rather as complementary means in the flood protection and control. The use and effectiveness of each method is often situation-dependent. Proper planning and preparation is always needed in order to achieve full efficiency.

Full-scale field testing is recommended for experimental verification of vital properties of each type of selected systems.

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DISCLAIMER

The information contained in this report is intended as a technology overview only to aid emergency preparedness planners, and is in no way intended as an official endorsement of one particular product or technology by the authors or sponsoring agencies. Opinions expressed are solely based on the information available to the authors at the time of preparing this report.

1. INTRODUCTION

Floods occur throughout Canada and world-wide. Flood damages exceed hundreds of millions of dollars a year. Despite large recent investments in hydro-technical works and flood alleviation measures the problem of flooding in Canada is not likely to diminish. With higher population density in flood prone areas, increased deforestation and land use changes, and even changing climate, the potential for property damage becomes higher.

Although conventional earth embankments provide cost-effective and reliable permanent protection against flooding, they cannot be used in all locations and, moreover, they must not be considered as an absolutely safe measure - the ultimate solution. These levees are designed for a certain height of flooding water characterized by a so-called “return period”: the longer return period, the higher design water level. Since the cost/benefit ratio limits embankment heights, this only means that increasing dyke heights merely postpones the occurrence of a flooding and, when it finally comes, the consequences can be even more severe in the absence of some other protection measures. Systems for temporary protection are thus necessary complementary tools in fighting against flooding. They may also be the only means of protection in areas that cannot be protected by conventional levees.

Sandbags have been traditionally used to build temporary barriers to hold back floodwaters. Several ingredients are critical to their success:

- the availability of adequate type and number of bags (maintenance of sandbag stockpiles has recently been passed on to local municipalities, and the current reserves are considerably smaller than historical ones),
- a readily attainable supply of filling material, shovels, transport vehicles, etc.,
- considerable manpower, with some training and experience to do the job properly,
- enough time for construction (installation of sandbag walls may be very time consuming).

A significant clean-up effort is necessary when the crisis has passed (probably the worst part of sandbagging is the huge amount of solid waste generated). Therefore, it is natural that there has long been a desire to find alternatives to sandbags that can overcome some or all of the above limitations.

2. OBJECTIVE AND SCOPE OF STUDY

The objective of this study was to evaluate innovative alternative methods to sandbags for temporary flood control and protection. When compared to sandbags, these alternative solutions should be:

- more easily installed and removed,
- sufficiently stable against sliding and overturning,
- resistant to seepage beneath (and through) them,
- flexible in use (to have possible other uses, not just as water barriers),
- cost effective.

3. REPORT CONTENT

This study is essentially a review of published literature and commercial brochures, with critical evaluation of available techniques based on common professional practice and gathered experience. It expands upon a recent report to the US Army Corps of Engineers WES (Duncan *et al.*, 1997), which examined various permanent and temporary flood control barrier systems, including additional information acquired during the research. Gathered data were sorted according to generic types of the systems; see Section 4.

The following aspects of each alternative are discussed and assessed (see Section 5 and Appendix 1 for more detail):

- stability with respect to sliding, overturning, seepage, durability in use, etc.,
- constructability, including simplicity of design, rate of construction, equipment and manpower requirements, terrain adaptability, etc.,
- costs, including capital acquisition, storage and maintenance,
- additional issues which were deemed important during the study (versatility in use and similarities).

The aim of the research was to arrive at a short list of a few most promising methods that are worthy of further detailed study and, possibly, eventual experimental or practical testing. These methods are presented in Section 6. Also included is a summary of strong points and problems with each selected method, stability calculations using a simplified approach (Appendix 1), information sheets for each method (Appendix 3), including addresses of manufacturers or distributors (Appendix 2), and other relevant information. The review of selected methods is completed with a few tables which present comparative data on these products.

Summary comments and recommendations for experimental verification and field testing are given in Section 7.

Two field trips to the towns of Peace River and Pincher Creek were undertaken during the course of the study, to discuss and evaluate actual situations and existing problems. These locations were selected as typical examples of the flooding conditions in Alberta:

- flash flooding, characteristic for the foothills of the Rocky Mountains in the south (Pincher Creek), and
- ice jam floods in the northern parts of the province (Peace River).

Observations gathered, and information provided by the officials met during these field trips, are incorporated in this report mainly through the weighting and proper ordering of evaluation criteria, as explained in more detail in Section 5.

4. COMMERCIALLY AVAILABLE SYSTEMS, BY TYPES

The alternative methods presented herein do not pretend to be exhaustive, although the authors believe that they cover the main types of currently available flood protection systems. New methods and adaptations and modifications of known systems continually appear, often under new commercial names. Sometimes it is difficult to trace the manufacturer and obtain complete required data on their products. This is particularly related to the data required for stability calculations - brand-new methods are sometimes advertised without complete documentation. In spite of that, there is no product in this report which was rejected because of insufficient data. Where a needed number or a description is missing, those fields are left blank or approximate values, or limits, are assessed and shown, believing that additional information may be furnished or appear later.

Original classification into distinct categories of only permanent and only temporary methods appeared inconvenient during the study. It is not easy to apply such a rigid separation to certain systems. The use and efficiency of a method is often situation-dependent. Certain planning and preparation is needed for even the simplest methods in order to achieve full efficiency. It seems that in many situations only a combination of certain techniques can give the best possible results. It is suggested that the responsible individual for flood protection chooses an appropriate method(s) by assessing local conditions and the application requirements.

The alternatives have been grouped into the following general classification (with some commercial suppliers listed below):

4.1 Cellular (gabion-like) barriers

Gabions are prefabricated flexible cellular structures (wire-mesh cages) filled with rock or soil on site. They have long been used in Europe as gravity retaining walls and, in hydraulic engineering, for lining the valley banks against stream erosion and raising of levees. Their use in flood protection was, therefore, chiefly as a permanent protection measure. There is very limited evidence of the use for flood fighting in emergency situations.

Another name for gabions in relevant literature is “deep cellular confinement”, which is coined mainly to differ them from “shallow cellular confinement”, i.e. shallow geogrid boxes (used in earth reinforced structures).

It is our opinion that this type of structure may be competently considered as a temporary protection structure, actually as a more efficient replacement of sandbag walls. This is particularly true for new products advertised by Hesco and Maccaferri, shown for illustration in Figure 4.1.1 and explained in more detail in Appendix 3. Essentially, these are collapsible multi-cellular structures, made of panels of wire mesh reinforced with vertical steel bars (Figure 4.1.2) which, when filled with soil, can provide earth structures like dykes. Flexibility of the metal cage and hinged structural connections enable good adaptation to local terrain conditions. Impermeability of the structures is achieved by geotextile liners and by the filler.

FIGURE 4.1.1 HESCO CONCERTAINER

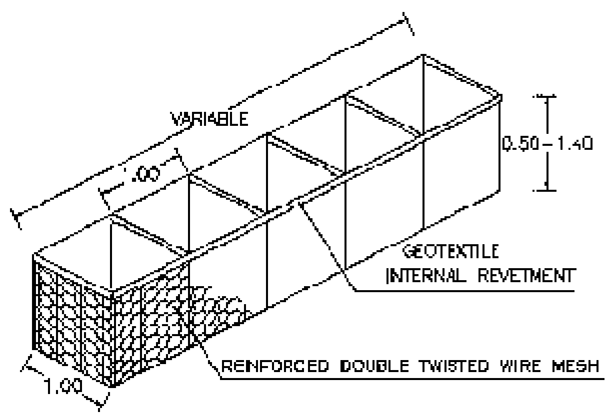


FIGURE 4.1.2 MACCAFERRI FLEX MAC

A variety of sizes and lengths in which these products are offered (Table 4.1.1) enables versatility in use - it is possible to obtain widely varying cross-sections and longitudinal forms - angles, multilevel walls, and extensions - by simply combining standard shapes.

This type of structure does not pose any constraints to the base soil, the relief, the filling material, etc. and can be relatively simply constructed on both level and sloping surfaces - length of cells can conform to site constraints, cells can be filled partially, etc. It is easy to support weak points by another cell on the back, or raise the height by adding another row of cells atop an existing wall. Problems sometimes may occur with overturning stability when cells are set up on highly sloping ground and filled with a loader. The factors of stability calculated in Appendix 1 are related to an ideal case of a horizontal flat base.

Type or commercial name	Length *L*		Width *W*		Height *H*		Maximum height of retained water H_w		Weight (empty)	
	(ft)	(m)	(ft.in)	(m)	(ft)	(m)	(in)	(m)	(lbs)	(kg)
Hesco Concertainer										
Mil 1B	32	10	3' 6"	1.1	4' 6"	1.37		1.10	344	156
Mil 2B	4	1.22	2'	0.6	2'	0.61		0.49	22	10
Mil 3B	32	10	3' 3"	1	3' 3"	1		0.80	231	105
Mil 4B	32	10	5'	1.5	3' 3"	1		0.80	352	160
Mil 5B	10	3.05	2'	0.61	2'	0.61		0.49	51	23
Mil 6B	20	6.09	2'	0.61	2'	0.61		0.49	99	45
Mil 7B	91	27.74	7'	2.13	7' 3"	2.21		1.77	2145	975
Mil 8B	32	10	4'	1.22	4' 6"	1.37		1.10	385	175
Mil 9B	30	9.14	2' 6”	0.76	3' 3"	1		0.80	222	101
Mil 10B	100	30.5	5'	1.52	7'	2.12		1.70	2332	1080
Maccaferri Flex Mac										
		1.5		0.5		0.5		0.4		
		5		1		0.5		0.4		
		5		1		1		0.8		
		5		1		1.4		1.12		

TABLE 4.1.1 STANDARD ASSORTMENT OF CERTAIN CELLULAR SYSTEMS

The simplicity of design is very strong point of this system. Unskilled labour can be employed for installation, with the only skilled labourer being the operator of the loader (Figures 4.1.3 and 4.1.4).

In the absence of installation machinery, or in the case of a saturated foundation soil that becomes deep mud under heavy construction machines, the cells can be filled manually by shovelling.

FIGURE 4.1.3 HESCO CONCERTAINER INSTALLATION: STRETCHING THE CAGE

Main advantages of cellular barriers over traditional sandbag dykes are in much less time and manpower required for filling and installation. Available commercial materials usually quote a US Army Corps of Engineers research which points out that the installation time is 10 to 20 times shorter and the manpower is 5 to 7 times less for the gabion installation than for sandbags. The example provided with Hesco Concertainer is related to a wall 1 m by 1 m in cross section and 10 m long. To build a sandbag barrier, 10 men have to fill 1500 sand bags working 7 hours. For the same wall made using Concertainer, 2 men will spend 20 minutes. These data assume the use of heavy equipment (e.g. front-end loader, mechanical digger). In the case of shovelling, the installation times and the labour requirements are probably similar for both sandbagging and cellular techniques.

They are easy to handle and transport (collapsed, in pallets). As an example, one kilometre of Concertainer cells can be transported on a single 40 ft articulated trailer.

It is worth mentioning that the storage requirements are significantly relaxed for gabion-like systems than for sandbags. When collapsed, they occupy less volume and, more important, they do not need closed storage space or sheltering. Usually, the cages are kept in pallets in the open air, since the wire mesh is galvanized and the geosynthetics is durable to weather action (Figure 4.1.5).

It is possible to reuse metal cages if they were not significantly deformed during filling and "loading" by flooding water. This is not the case for larger units, where soil pressure of the filler is high enough to cause plastic deformation of the mesh and even corner steel bars. Also, when a few rows of gabions are stacked one over another, lower rows are deformed to such an extent that they can not be used again.

4.2 Concrete (or metal) removable barriers

Several types of these defence structures were found in the references. These are traditional removable civil engineering structures, with various structural systems and installation procedures. Some of them seem to have very limited application in flood protection area, while others may show certain advantages in specific circumstances. In the following text, available systems are explained separately from one another due to mentioned differences.

FIGURE 4.1.4 HESCO CONCERTAINER

Installation : Mechanized filling

FIGURE 4.1.5 HESCO CONCERTAINER

Storage: folded gabions

4.2.1 RICHARDSON’S CONCRETE AND STEEL BARRIERS

These structures are named after their inventor. Their primary use has been as barriers for flood protection of highways in the United States.

The concrete type is shown schematically in Figure 4.2.1, borrowed from Duncan *et al.* (1997). It consists of prefabricated reinforced concrete elements, produced with heights of approximately 0.75 m (30”) and 1.50 m (60”). These elements can be stacked one row over another. The connections are made using bolts and clamps, with compression gaskets for impermeability. Heavy equipment is needed to lift and place the elements. The resistance against water pressure is based on gravity, i.e. the weight of elements.

The steel version of this structure is shown in Figure 4.2.2, borrowed again from Duncan *et al.* (1997). It consists of steel sheets supported by steel or wood bracing. The elements are made with heights of about 0.9 m (36”) and 1.2 m (48”), and are 2.4 m (8 ft) in length. These elements can be stacked one over another, and over a base row of concrete elements. The connections are made using bolts and clamps. There is no need for heavy equipment in their installation. Stakes are needed to stabilize the steel barrier to foundation soils.

Stability factors against sliding and overturning were not calculated due to the lack of data, but it is assessed that they may be very low because of almost vertical angles of panels on the wet side, and almost horizontal action of water pressure. In Duncan *et al.* (1997) the value of the factor of safety against sliding is below 1, but the input data for this calculation are not given. The problem with these structures is in their support by the base soil, since a dominant portion of the resultant force is transmitted to the soil by the rear leg. The “footing” contact area is small and resulting bearing pressure is high, limiting the use of this structure to strong foundations - very stiff soils and rocks (or actually roads, as it was designed for). This is even emphasized by the requirement of heavy equipment for installation.

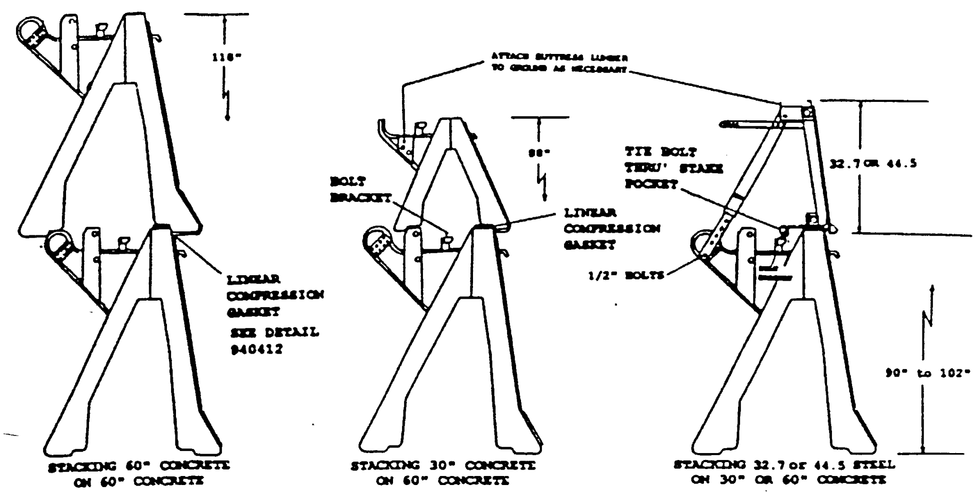
There is no seepage through the structure, but seepage gradients under the barrier are inadmissibly high; Duncan *et al.* (1997) have calculated the range from about 0.5 to 4.0. Therefore, the problems may rise with soft and loose soils. It is not quite clear how the system can handle varying terrain (leakage below the barrier) using geomembrane sheeting anchored at the end of the sections, as quoted in the reference.

The structural system itself is very complicated for unskilled users and training is required. The method needs heavy equipment for installation and is labour intensive. Certain preparatory works are necessary - levelling of the ground where barriers will be placed. Heavy transportation vehicles are required for the concrete version. Strong points of the system are variable height and the capability of making corners (turns) in plan, as well as durability in use.

Initial (purchase) cost is high. Storage space is extensive for the concrete variant and significantly less for the steel one (sections can be placed flat). What is most important is that the system has not been tested yet - there are no references on its behaviour in flood protection practice.

This method has not been evaluated in more detail. It was concluded that its area of application is severely limited and that it can not be recommended as a general flood protection measure.

FLOOD BARRIER STACKING METHODS



FLOOD BARRIER STACKING METHOD

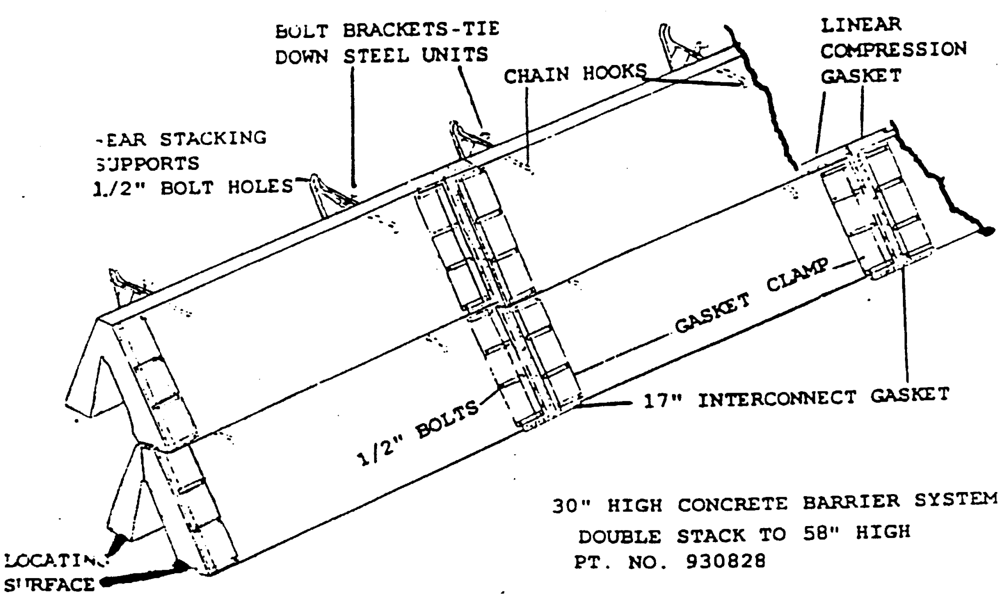


FIGURE 4.2.1 RICHARDSON'S CONCRETE FLOOD BARRIER

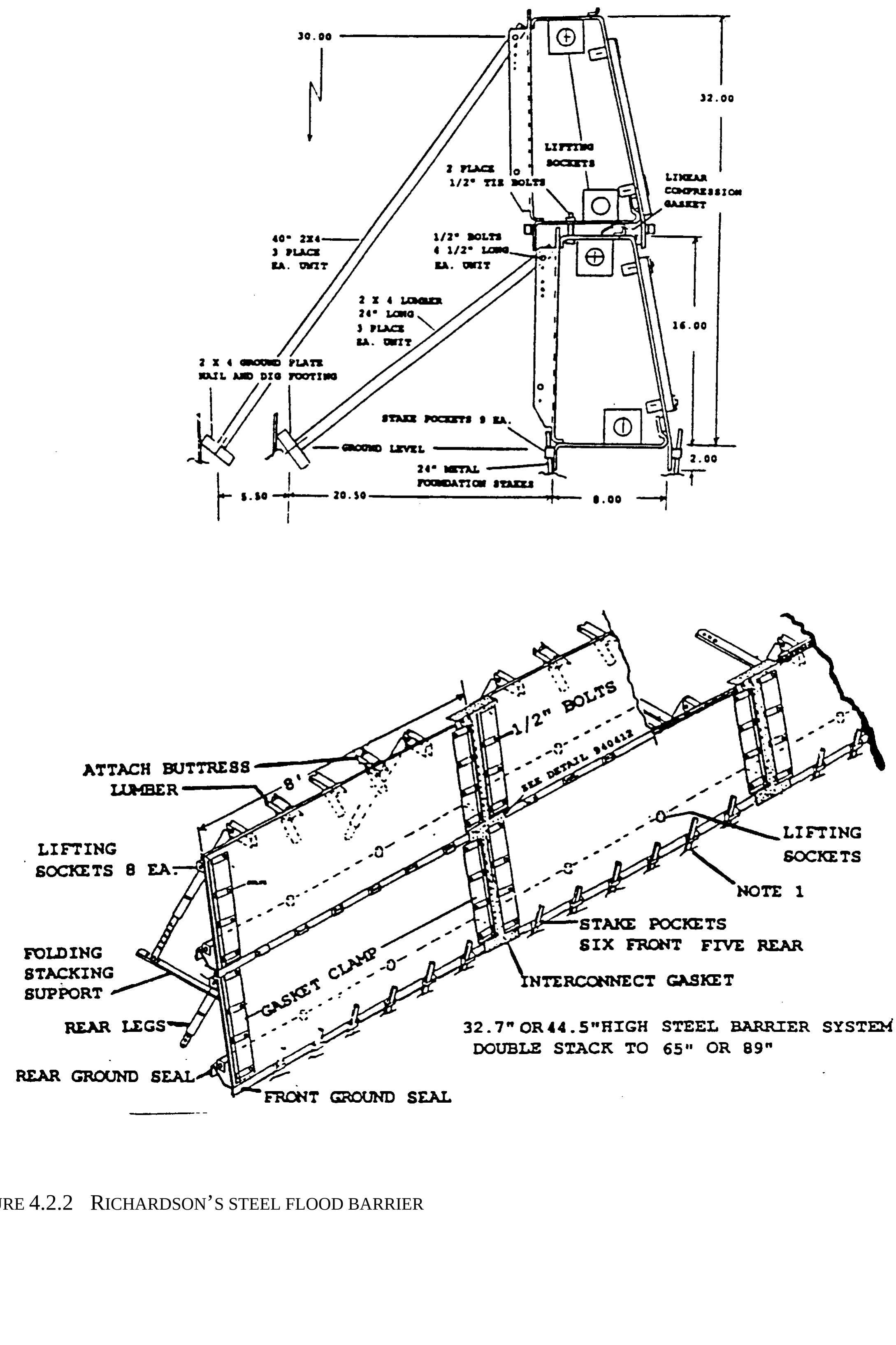


FIGURE 4.2.2 RICHARDSON'S STEEL FLOOD BARRIER

4.2.2 JERSEY HIGHWAY BARRIERS

Jersey highway barriers are precast reinforced concrete elements which can be combined with polyethylene sheeting in order to form a hydraulic barrier. They are made in a single shape and size: 0.8 m (32") high, with the base 0.6 m (24") wide, and 3 m long, as shown in Figure 4.2.3. The height of retained water is about 0.5 m for a single row system. It can be increased to about 1.5 m by stacking Jersey barriers in the way shown in Figure 4.2.4. Jersey barriers have long been used for flood protection in the United States because of wide availability, especially in rural areas (Duncan *et al.* 1997).

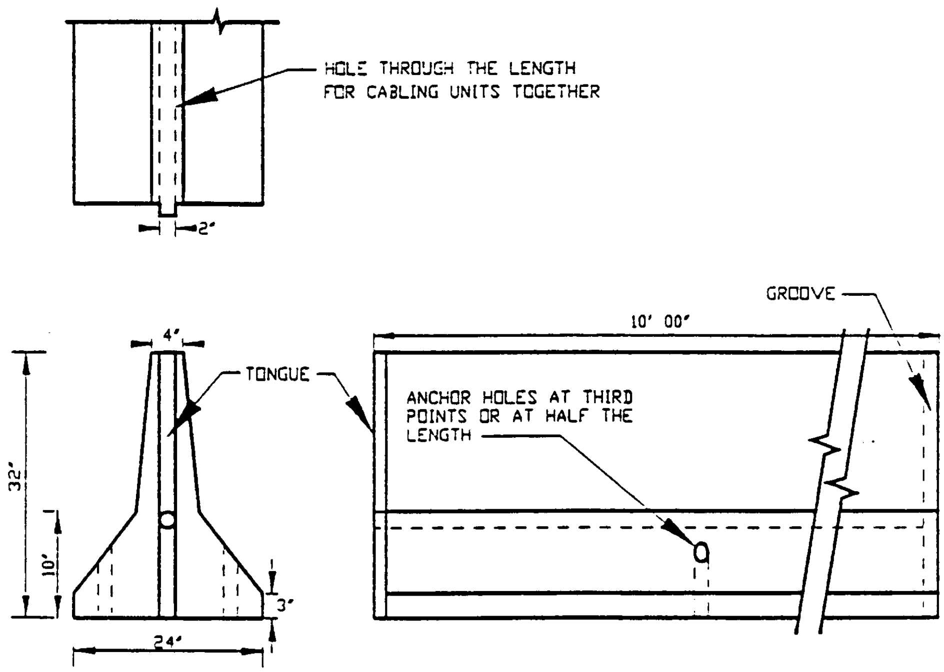


FIGURE 4.2.3 JERSEY HIGHWAY BARRIERS – SINGLE UNIT

The factor of safety against sliding calculated in Appendix 1 is marginally over 1.0 for a soil with the friction angle of 15^0 and a single row barrier. The same factor of safety $F_s = 1.0$ for full uplift on the base (after a gap has appeared) requires the soil with at least 22^0 of friction angle, thus indicating potential instability in real conditions (flowing water with wave action). Design improvements (Duncan *et al.* 1997) have been made to remedy the problem (see Figure 4.2.3): connections in the form of tongue and groove, holes for anchoring using metal stakes, etc. It seems also that certain improvements may be achieved if the sheeting is laid in front of the unit, as a kind of impermeable blanket (Figure A.1.3). The vertical uplift pressure is reduced in such a way and the overall stability of the barrier increased.

The calculated average hydraulic gradient below the structure is about 0.8 (Appendix 1), which is a high value, but may be reduced, depending on the length of impermeable blanket. Leaking at joints is prevented by seaming (tongue and groove joints) and sealing - wrapping the elements by geomembrane sheeting. A weak point is that it can not make corners (turns) in plan.

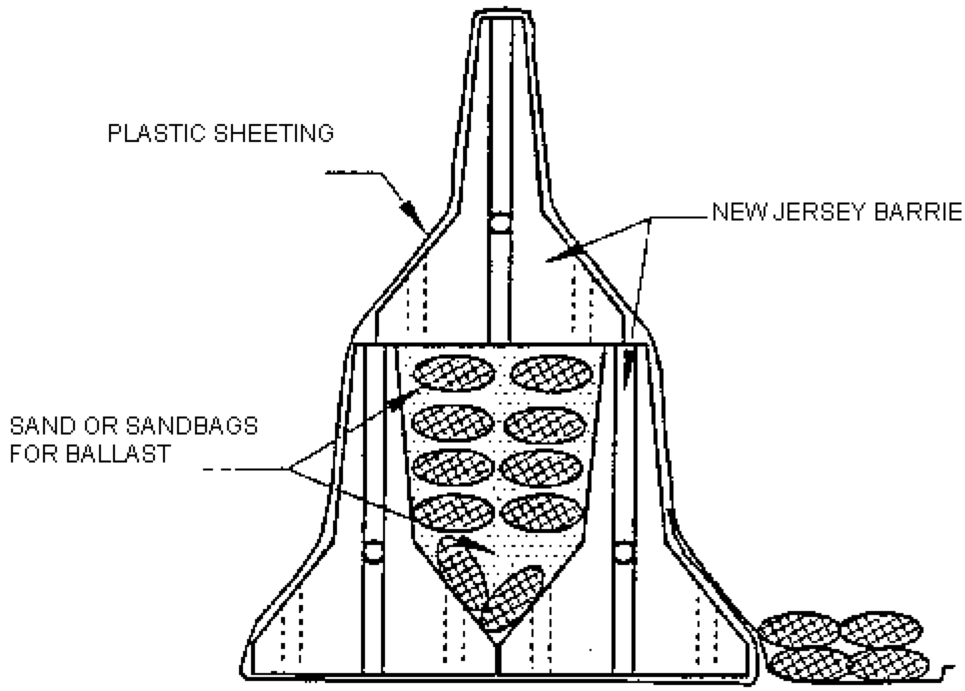


FIGURE 4.2.4 JERSEY HIGHWAY BARRIERS – STACKED UNITS

The structure itself is very simple and fast to install, although it requires the use of heavy equipment (i.e. small forklift). This may limit its feasibility to strong soil and rock surfaces, as well as to urban areas because of the access required by heavy transportation vehicles.

Certain benefits appear with costs. Assuming that the elements are already available, there is no initial investment. The system (concrete elements) does not need storing. There are no damages in use, as well (polyethylene sheeting is considered expendable goods here). On the other side, there are expenses for engagement of heavy trucks and installation equipment.

In conclusion, applicability of this method is spatially limited to the areas where Jersey highway barriers already exist, and to urban zones or close to the places where Jersey elements are held. Its use is best suited for flat terrain and long straight barriers because of difficulties in achieving turns (corners).

4.2.3 PORTADAM

Portadam is a steel framed structure faced with geomembrane sheeting that extends beyond the toe of the frame, see Figure 4.2.5. The system is a semi-permanent structure because it requires small concrete foundations in the ground for steel frame supports. The installation consists of placing the frames at about 0.35 m (15”) spacing, bolting them, anchoring legs, placing geomembrane sheets and then weighing them using sandbags, rock blocks, etc. The structure is available in heights of approximately 1.5 m, 2.1 m and 3.0 m (5, 7 and 10 ft). It has a successful record in flood fight situations, mainly for individual industrial objects (Duncan *et al.* 1997).

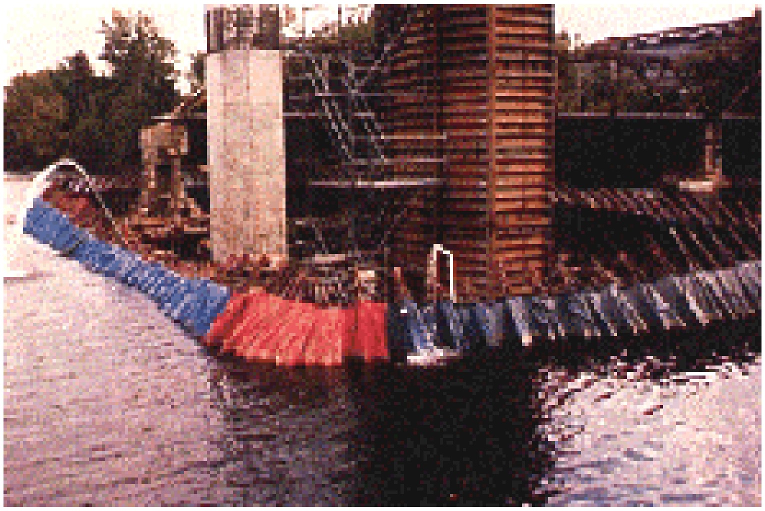


FIGURE 4.2.5 PORTADAM – PROTECTION OF A BRIDGE PIER CONSTRUCTION SITE

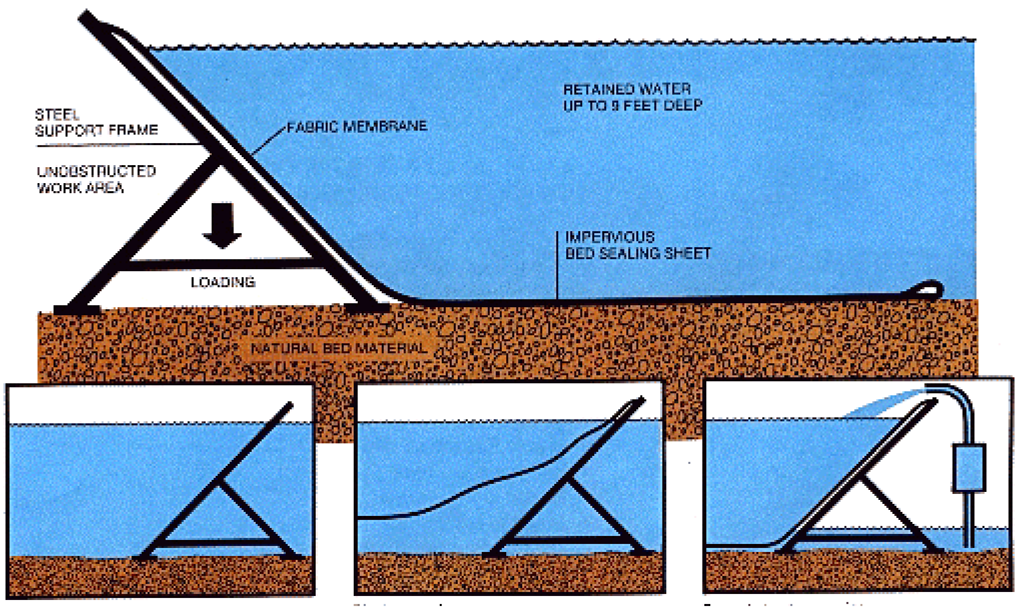


FIGURE 4.2.6 PORTADAM: THE STRUCTURE (ABOVE) AND INSTALLATION INTO THE STATIC WATER (BELOW)

Stability factors against sliding and overturning were not calculated due to the lack of data. It is even questionable how they are to be calculated. It is assessed that the sliding resistance is completely determined by the size of concrete foundations and soil properties (it is not clear how Portadam behaves without foundations). In Duncan *et al.* (1997) the value of the factor of safety against sliding is about 0.6, but the input data for this calculation are not given. An inclined wet side of the structure introduces a vertical component of the water pressure into the foundation, increasing the sliding resistance in this way. The resultant force is highly eccentric to the footprint area and the dominant portion of the resultant is transferred to the soil by the rear legs and their foundation.

Seepage through the ground does not seem to be an issue since (at least, in theory) the hydraulic gradient may be decreased by increasing the length of geomembrane placed as a blanket in front of the barrier. However, the problem may be with the leaking through the barrier because the seams between the plastic sheets appear to be by friction only. Available reference material does not describe how plastic sheeting behaves in the case of fast flowing water (if there is fluttering, twisting, etc., which is particularly important for the part laid on the ground). Also, it is not clear whether there can be leaking between the ground surface and the membrane, which is not absolutely flexible and therefore may leave certain gaps to the soil, even when it is pressed by flooding water above it. Figure 4.2.5 shows significant amounts of seeped and leaked water which is pumped back into the river.

The structure itself (Figure 4.2.6) is well designed: it is lightweight and may be installed by hand. It allows for changes in alignment (corners are easily made) and terrain. A significant advantage is that it can be placed both in the dry and static water conditions (the water behind the dam is then pumped out). On the other hand, the installation procedure is not so simple and requires trained manpower. It is labour intensive because of many parts and connections. It also needs preparatory works - the concrete foundations.

Initial investment is high for the Portadam. It also needs significant storage space. Durability of the membrane in use may be a problem, too. The vinyl liner is reinforced, but is subject to puncture and damage by the floating debris. If thicker and heavier membranes are used for better protection against floating debris, they are stiffer and harder to handle.

Despite certain strong points of this system, and successful experience in flood fighting situations, it is our estimate that it is most suited to urban areas and industrial users for protection of their own important sites.

4.3 Fixed post-and-lagging systems (stop-log dykes)

Fixed post-and-lagging systems, or stop-log dykes, are based on a simple and clear idea, as illustrated in Figure 4.3.1. Hollow members, lined with rubber gaskets, are placed horizontally between vertical steel H-piles.

These structures have been used for flood protection in Europe (mostly in Germany - GOH DPS 2000 system) and for some time in the U.S. (with much success). In the Duncan *et al.* study (1997) they were categorized as permanent flood control structures and were rated the best in that group. A permanent foundation is required, but the metal structure can be dismantled and stored when it is not in use. This feature is what enables us to consider post-and-lagging systems equally well as a temporary flood protection structure in specific circumstances.

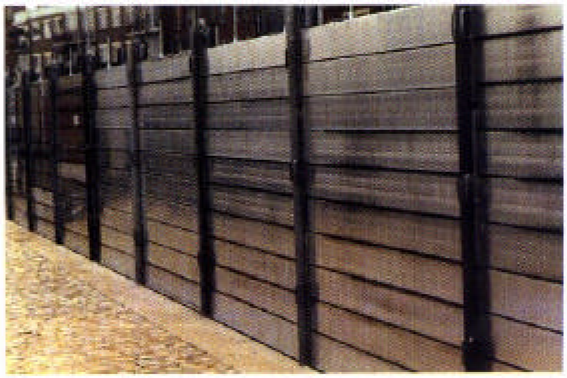


FIGURE 4.3.1GOH DPS 2000 SYSTEM

FIGURE 4.3.2 GOH DPS 2000 SYSTEM: ADJUSTABLE HEIGHT

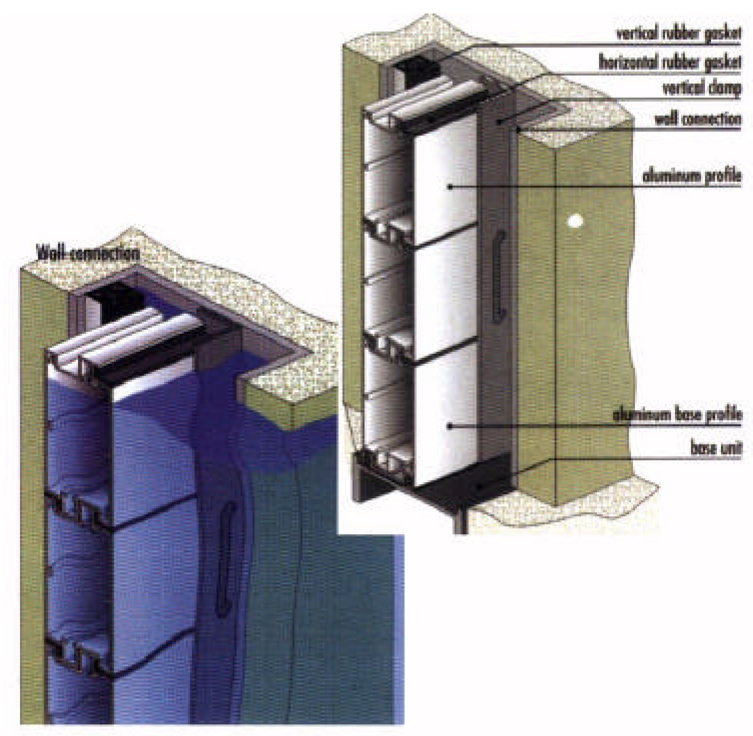


FIGURE 4.3.3 GOH DPS 2000 SYSTEM: SEALING

The structure may be installed on the top of existing stable wall, along the edges of a concrete slab, etc.; otherwise, a solid concrete foundation must be constructed. Metal bearings for posts are made and protected by checker plates. H-piles are fixed using bolts and additionally supported by inclined beams having an adjustable foot to properly lay onto the ground. H-piles are galvanized to protect them from rust. Light hollow aluminium members are then dropped in place between the posts. The height of barrier is easily increased if the water level behind the wall rises - there is no wasted effort (Figure 4.3.2). As well, each section is statically independent and the wall may be constructed in any order.

With this structure there are no problems with sliding and overturning stability, assuming that host structure is stable by itself. Also, there are no problems with seepage and leaking through the wall: Figure 4.3.3 shows sophisticated water-tightening sealing. Seepage through the soil depends on the foundation structure for this system; it is recommendable that the criterion for average hydraulic gradient from section 5 and Appendix 1 be checked in every particular case.

The structure is easy to install (Figure 4.3.4), although minimal training of the staff is required. The construction is not labour intensive and no equipment is needed. It is also very expedient: according to manufacturer's brochure (GOH system), only 3 men can construct 150 m long wall, 1.8 m in height, in 5 hours. Actually, 3 people are required only for heavy vertical pile erection. Placing horizontal aluminium members is a one-man job because of their lightness (3.0 m long member weighs only about 20 kg).

The cost of this structure is very high, compared to other methods, mainly due to expensive materials (aluminium) and the need for large, secured storage space (to protect against theft), as well as necessary preparatory works. This is partly compensated for by its durability in use - longevity and low installation costs.

This system is highly recommendable for important objects, as a closure structure. Also, its use may be justified in densely populated urban areas, where access to a river should be preserved (i.e., dykes must not be built), the ways of flooding water are well known and the protection length is not too long. In such a case, this structure may serve as a hidden flood control system along river banks.

4.4 Water-filled (or air-filled) geomembrane tubes or plastic elements

Water-filled geomembranes are relatively new products in flood control and hydraulic engineering in general. They are based on the idea to use water itself to make barriers - dams which will retain the flood. Usually, these systems use stream water to fill prefabricated geomembrane tubes or segments of various shapes and sizes and make a dam. The success and rapid recent spreading of these systems is mainly because of their speed of installation and simplicity.

Various commercial products, available and advertised, are a reflection of different ideas in this field. Many of these products are still in developing stages, with no defined assortment and pricing, as well as without extensive testing or experience in flood fighting. Certain systematization is thus needed in the beginning.

Firstly, these systems may be sorted according to the shape of the basic element:

- cubicle or "brick-like" systems, which include "Water Wall" and "SWI Mitigation HDPE Blocks"; and
- tubular systems, which describes the remaining products noted in this section.

FIGURE 4.3.4 GOH DPS 2000 SYSTEM: INSTALLATION

FIGURE 4.4.1 WATER WALL SYSTEM

Water Wall system uses prefabricated flexible PVC elements of a trapezoidal shape, shown in Figure 4.4.1. “SWI Mitigation HDPE Blocks” are thick-walled polyethylene blocks that are interlocked and filled with water on-site, Figure 4.4.2. Since both systems differ from the tubular ones with respect static action and installation procedure, they will be explained in separate sections.

Tubular systems may further be divided into 3 types:

- water-filled “effectively single” tubes, with two subtypes: one consisting of inner tubes encompassed by an outer “master tube” of reinforced high strength plastic (“Water Structures” and “Aqua Dam”), and another having a single high strength outer tube with internal baffles (“Aqua-Barrier”);
- water-filled multiple tubes (“Clement Water Diversion Systems”); and
- air-filled tubes (“NOAQ Flood Fighting Systems”).

Tubular systems are very similar in design, requirements and behaviour and will be described as a group in the following text.

It should be noted that there is a whole other group of similar structures called “rubber” or “inflatable dams”, consisting of a single air-inflatable rubber bladder anchored to a concrete foundation. Rubber dams have long been used in hydraulic engineering as permanent water barrages, mostly in the Far East (Sumigate of “Sumitomo Electric Industries” from Japan, as the main type). Such structures are not encompassed by this report.

4.4.1 WATER WALL

The Water Wall system is shown in Figure 4.4.1. The system design seems more efficient than in other structures of this type: the sloping face uses the vertical component of the water pressure as an additional stabilizing force (normal pressure to the ground to increase the friction). It is lightweight - sections are about 60 kg, and flexible - conforms to the terrain. Significant disadvantages are that it is produced with only one cross-sectional size and height of 1 m, and that it can not be stacked. These are serious limitations in its application: low retained heads of flooding water - less than 1 m - are allowed.

Sliding and overturning stability could not be calculated due to the lack of data. Seepage through the ground is controlled by an attached impermeable blanket which reduces the maximum hydraulic gradient. Leaking between sections seems a problem - seaming between them is not predicted, and watertightness of these “contact joints” is questionable.

Installation procedure consists of two steps: an element is first inflated with air, to give the designed shape, then the air is displaced by water. The construction is simple and expedient, there are no requirements for machinery and a few labourers are needed. There are no preparatory works, except for minimal removal of sharp stones, roots and branches, etc.

The prices were not available so that initial investment could not be calculated. Required storage space is small - the manufacturer’s data are 10 deflated sections per truck. Durability in use was not addressed, but there is danger of puncture by flowing debris (as with other inflatable geomembranes too). There is also serious concern about the reliability of such a structure - one can not see how it would be possible to replace on site an element which has been punctured and deflated.

The references on system application were not provided.

In conclusion, because of the above limitations this system will not be considered as a method of further interest.

4.4.2 SWI MITIGATION HDPE BLOCKS

The system is shown in Figure 4.4.2, taken from Duncan *et al.* (1997). Building “bricks” are shaped so that can be put together in only one way (“idiot-proof” design). They are portable - their weight is about 45 kg each. It is possible to make turns in plan (corners). The connections between elements allow water flow from segment to segment which facilitates their filling. The height of structure is advertised as “unlimited” although only 1 m has been observed during a sponsored presentation (Duncan *et al.* 1997). Pronounced deformation of the bottom layer was noticed when height was increased over 1 m.

Segments can be anchored through 2 portholes in each section. This is probably because of the low sliding resistance due to the flat bottom design. It is also questionable whether this structure is flexible enough to conform well to uneven ground.

Seepage below the structure may be a concern - it seems that nothing has been anticipated to reduce the hydraulic gradient through the ground. Placing an impermeable membrane on the wet side may prevent leaking through the joints.

The installation procedure is fast and straightforward, limited manpower is required, although some training or skill of the labourers seems necessary. Problems appear with transport, because elements must be transported to the site in bulk, as well as with huge storage space required.

Purchase cost is high because of the number of elements necessary. The same is valid for the storage. Lifetime is limited to 7 years, although the elements are ultra-violet and chemically resistant (this point is not clearly explained by the manufacturer).

There are no examples of application in flood protection.

This method was not considered feasible for general application due to the above mentioned problems with the design solution, transportation and storing.

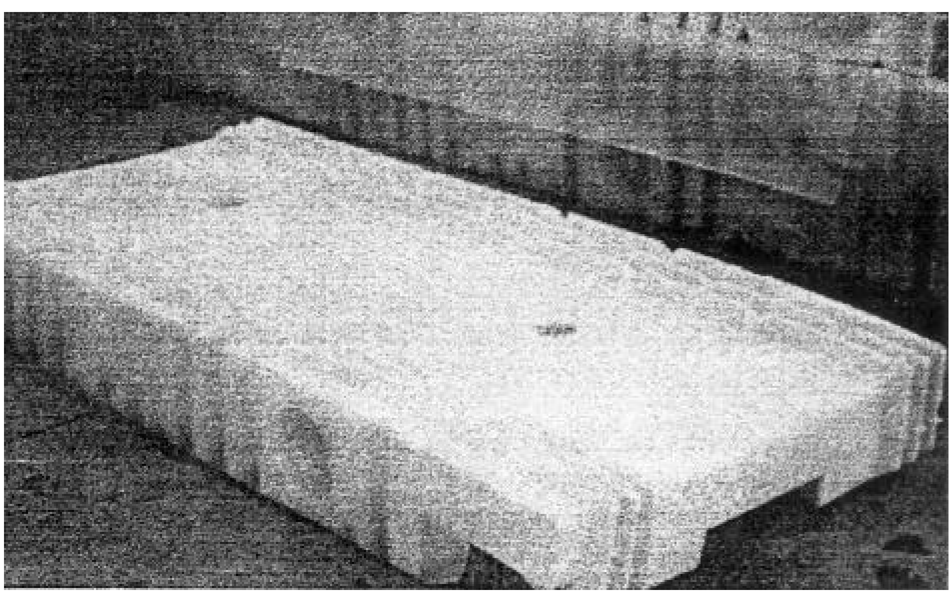


FIGURE 4.4.2 SWI MITIGATION HDPE BLOCKS

4.4.3 TUBULAR SYSTEMS

4.4.3.1 Water-filled tubes

Water-filled geosynthetics tubes are actually portable gravity dams (Figure 4.4.3). The weight of water provides stability against sliding. Since the shape of an inflated tube is somewhat irregular - asymmetric under the pressure of retained water, the calculation of the factor of safety in Appendix 1 is based on crude simplifications and should be verified experimentally.

A real problem with this type of system is not sliding, but “overturning stability”. Calculating a factor of safety against overturning is senseless because the tube is too flexible, and torsional deformation caused by horizontal pressure of the flood water may be so large that the tube can change its shape and actually roll like a car tire. Such a deformation is greatly emphasized under the wave action of the water. Some kind of anchoring is, therefore, necessary for stability against rolling. External anchoring would be complicated to carry out in reality. Another option is to apply a kind of “internal anchoring” - to design the tube so that it possesses higher torsional stiffness, which reduces corresponding torsional deformation and, in that way, actually prevents itself from rolling. Different designs of these systems are shown in Figures 4.4.4 and 4.4.5.

The solution chosen by designers of “Water Structures” and “Aquadam” systems (Figure 4.4.4) is based on two internal tubes, which are filled with water, wrapped by one outer tube. Inner tubes are constructed of softer, flexible material (e.g. 10 – 16 mm thick polyethylene is used for “Water Structures”), but the outer, “master” tube is made of a durable, reinforced, stiffer material (woven plastic fabric in the case of “Water structures”). Friction between internal tubes prevents them from rolling with respect to each other, and the outer tube provides circumferential force and external stability. “Aqua-Barrier” uses one or more internal restraint baffles for the same purpose. The tube is manufactured from industrial grade vinyl, reinforced with polyester.

The “Clement” system (Figure 4.4.5) employs a generic idea: multiple tubes are secured together by belts making a shape which is pyramidal in cross-section and, therefore, unable to roll. A tube is made of vinyl coated polyester with a single - standard size: 17.5 inches (about 44 cm) in diameter and 50 ft (15 m) in length. Dry weight is about 50 lbs./tube, i.e. about 23 kg per tube.

Additional support against sliding may be provided by earthen levees on the dry side of the tube, for each of above mentioned structures.

Induced loading on the soil is calculated in Appendix 1, again in an approximate way. It is low for small tubes (and low water levels), but increases with the retained water heights and may become too high for saturated soft soils. The feasibility of the system should be checked for every particular case.

Seepage gradients in the soil are generally quite small – about 0.3 to 0.4 (Appendix 1). There is no leaking through properly constructed barrier: “Water Structures” apply special collars to seal the joints, and the others have similar connection solutions. The “Clement” system uses separate “sleeves” for each of the tubes in a cross section. The tubes in a connecting sleeve are overlapped so that, when they are inflated, they lock each other by friction and cannot be pulled out.

These systems have certain general design advantages:

- they are produced in widely varying standard sizes (Table 4.4.1): diameters typically up to 1 m, but may be specially ordered with diameters up to 3 m, and lengths typically 15 m and 30 m, but again may be specially ordered in arbitrary lengths;

FIGURE 4.4.3 TUBULAR WATER-FILLED STRUCTURES: PORTABLE DAMS ("WATER STRUCTURES")

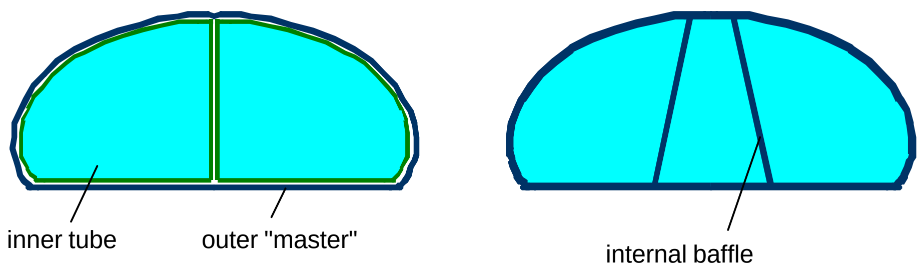


FIGURE 4.4.4 VARIOUS CROSS-SECTIONS OF TUBULAR WATER-FILLED SYSTEMS: INTERNAL AND EXTERNAL TUBES: "WATER STRUCTURES" AND "AQUADAM" (LEFT); INTERNAL BAFFLES: "AQUA BARRIER" (RIGHT)

FIGURE 4.4.5 VARIOUS CROSS-SECTIONS OF TUBULAR WATER-FILLED SYSTEMS: "CLEMENT" SYSTEM

Type	Length L		Width W		Height H		Maximum height of retained water H_w		Weight (empty)	
	(ft)	(m)	(ft)	(m)	(ft)	(m)	(in)	(m)	(lbs)	(kg)
Aqua - Barrier										
Single Baffle	100	30.5	4	1.2	2	0.61	18	0.46	200	91
			7	2.1	3	0.92	27	0.69	375	170
			10.5	3.2	4	1.22	36	0.91	500	227
Double Baffle	100	30.5	7	2.1	3	0.91	27	0.69	375	170
			10.5	3.2	4	1.22	36	0.91	667	303
			13.5	4.1	5	1.52	45	1.14	874	397
			17	5.2	6	1.83	54	1.37	1000	454
			20.5	6.2	7	2.13	63	1.60	1167	530
Aqua Dam										
AD15	100	30.5	3	0.91	1.5	0.43				
AD02			4	1.2	2	0.61				
AD03			7	2.1	3	0.91				
AD04			12	3.6	4	1.2				
AD06			20	6.1	6	1.8				
AD09			34	10.3	9	2.7				
Water Structures										
WSU 12-24	100	30.5	2.0	0.61	1	0.31	8	0.20	100	45
WSU 18-36			2.7	0.81	1.5	0.46	12	0.30	113	51
WSU 24-48			3.8	1.17	2	0.61	18	0.46	150	68
WSU 36-72			5.7	1.73	3	0.92	28	0.71	260	118
WSU 48-105			10.0	3.05	4	1.22	36	0.91	400	182
WSU 72-156			15.5	4.73	6	1.83	54	1.37	900	409
WSU 102-220			19.3	5.90	8	2.44	72	1.83	1790	813
NOAQ										
		20			2	0.6		0.5		50
Water Wall										
	16	5	5	1.5		1			115	59
Clement										
Single tube	50	15					8	0.2		20
2 tubes in a single level							16	0.4		41
2 levels							26	0.65		62
3 levels							36	0.91		122

TABLE 4.4.1 STANDARD ASSORTMENTS FOR CERTAIN TUBULAR WATER-FILLED SYSTEMS

- it is possible to make corners at arbitrary angles using flexible couplings (Figure 4.4.6) – so it is good for closure structures;
- it is easy to increase the height of the structure temporary, either inflating the tube by simple pumping, or adding a new row of tubes, as in the case of "Clement" systems (caution is recommended in such cases because of decreased stability against rolling);
- they are very flexible and easily accommodate to almost any terrain (downstream sloping sites can be problematic - there is not enough data provided) - equally good in urban and rural areas,
- small preparatory works (essentially none) required - cleaning of sharp stones, roots and branches, etc.;
- they are reusable and durable in use - manufacturers describe an easy procedure of tube fixing after puncture, which can be done in use, on-site (another, even simpler, option is to continue pumping, in order to compensate for the water loss through the cut);
- they are versatile and may be used for various other purposes: temporary reservoirs for other liquids, dewatering work sites, aquatic pollution containment, etc.

Weak points are:

- durability to puncture (floating debris);
- excessive flexibility of large diameter tubes;
- rolling stability problems with long straight stretches (anchoring of intermediate sections is needed);
- rolling stability is questionable under the wave action;
- large base width to height ratio (about 3) may be inconvenient in certain urban areas;
- large quantities of water for filling the system should be available on the site - urban locations or closeness to streams are preferred;
- low temperature can sometimes cause freezing of the filled tubes - any attempts to move them may cause ice breaking and its sharp edges may damage the tube.

The installation time is very short compared to other systems. As an example, "Aqua-Barrier" quote the data from the U.S. Army Corps of Engineers study for comparative construction of a sandbag wall 3 feet high and 100 feet long, and installation of their structure of the same size. The time for sandbags was about 4 hours (with a group of 5 people), while the "Aqua-Barrier" took only 20 minutes. These data are likely to be too optimistic in the case of real conditions. More reliable data is found in the "Water Structures" Manual which specifies from 1 to 1.5 hours for the tube 4+ feet high and 100 feet long.

The procedure of installation is intuitive and does not require skilled personnel, although certain experience is necessary for optimal performance, especially for larger diameter tubes. Also, there is no need for heavy machinery, neither for transport nor for installation (with the exception of some heavier models, for higher water levels - Table 4.4.1). A couple of portable pumps and a few labourers, depending on the size of the tube, is all that is needed.

According to the manufacturers' information sheets, problems appear with installation in flowing water, which requires much more people, time, skill and experience. This was not taken as a disadvantage because other systems described in this report can not routinely be installed in such conditions.

FIGURE 4.4.6 TUBULAR WATER-FILLED STRUCTURES: FLEXIBILITY, CORNERS, TUBE COUPLING ("AQUA BARRIER")

FIGURE 4.4.7 TUBULAR WATER-FILLED STRUCTURES: "CLEMENT" SYSTEM INSTALLATION

There is a particular advantage in installation of the Clement system over the other water-filled plastic tubes. The modularity of the system makes it easier for construction: each tube can be carried by hands to the site and assembled there into the structure (Figure 4.4.7). The other systems are made in one piece (tube) and some of them are heavier than what two people can carry by hand (100 kg and more).

Initial cost of these systems is high, but tubes are reusable. Closed storage is necessary (in general, although various products have different sensitivity to sunlight, low temperatures and chemicals), but the area is not large. Durability in use is not clearly defined in available commercial materials, so that maintenance expenses can not be estimated.

Installation and removal costs are small for lower retained heads. Quoting again the study of the U.S. Army Corps of Engineers and the example of a sandbag wall, 3 feet high and 100 feet long, and a comparative “Aqua-Barrier” system, the former costs about US$ 10,200, but the latter is slightly over US$ 3,100.

Examples of successful application of these systems for flood control are provided by their manufacturers – see, for illustration, Figure 4.4.8 and 4.4.9. Nevertheless, it seems that additional verification is required in different natural conditions and more experience should be gathered with individual products.

In conclusion, water-filled geomembrane tubes are viable systems for flood protection in various conditions, both urban and rural ones. It is also well suited for closure structure and individual object protection. More experience is needed for higher retained water levels - more than 1 m. Also, the behaviour in dynamic conditions, with fast flowing water, should be tested and evaluated.

4.4.3.2 Air-filled tubes

The only product of this type is NOAQ system, shown in Figure 4.4.10. The basic idea is very interesting: since the tube is practically weightless, anchoring of the wall completely relies on the flood water pressure making use of a skirt - blanket, fused to the tube and laid down onto the ground in front of the barrier. Practical realization of this idea is shown in Figure 4.4.11. Some sophistication in the design of the blanket includes a drainage layer (possibly of a stiffer geonet) to ensure maximum possible action of differential water pressure. This, however, may result in increased rate of leakage beneath the wall, following the path through the drainage layer, although it need not necessarily be the case. The dominant effect in low permeability soils is, most probably, only decrease of the water pressure under the blanket, with the amount of leaking water negligible for all practical purposes (especially for short-term floods).

The structure is very light: a 10 m long and 60 cm high section weighs less than 50 kg. It can be easily handled by only two persons. The tubes can be attached at different (arbitrary) angles - corners are possible.

Seepage gradients through the ground may be adjusted (reduced) by proper lengths of the skirt. Leaking through joints is also very easy to solve, since the tube connections are not stressed (they do not transmit any significant forces) and, actually, the tube ends do not need to be physically connected at all. The impermeability of the joint is provided by a separate blanket attached to the skirts of the two adjacent sections by ordinary zippers. Some straps are used to prevent the blanket from being pressed by the water pressure through the gap between the tubes, since this may strain the zipper.

FIGURE 4.4.8 TUBULAR WATER-FILLED SYSTEMS: EXAMPLES OF APPLICATION “AQUADAM”

FIGURE 4.4.9 TUBULAR WATER-FILLED SYSTEMS: EXAMPLES OF APPLICATION “WATER STRUCTURES”

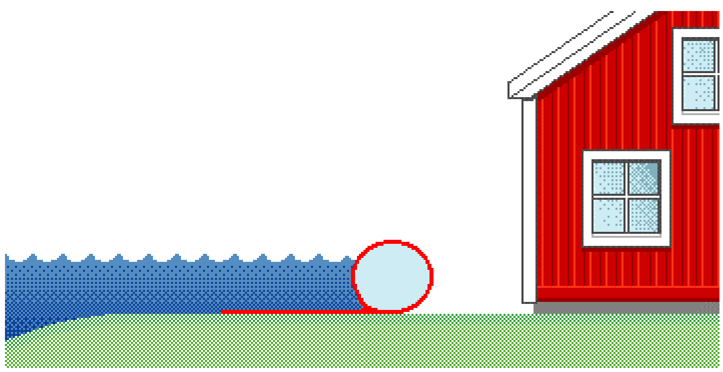


FIGURE 4.4.10 AIR-FILLED TUBULAR STRUCTURES: NOAQ SYSTEM

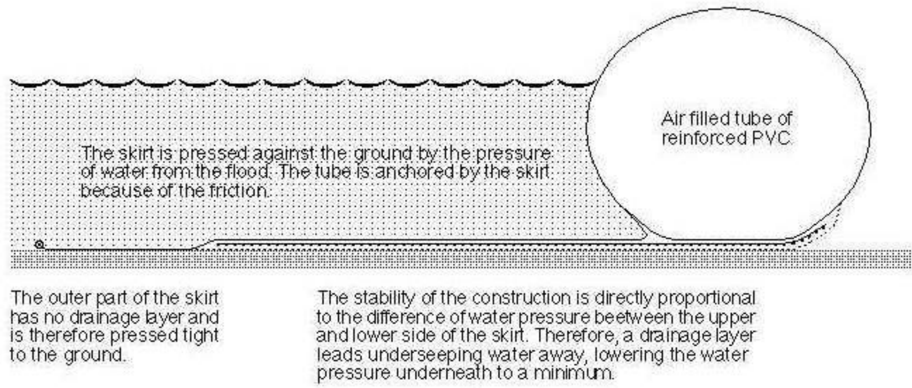


FIGURE 4.4.11 AIR-FILLED TUBULAR STRUCTURES: NOAQ SYSTEM – THE PRINCIPLE

The system was tested on gravel, grass, concrete and asphalt surfaces with equal success, according to the manufacturer.

This is all the information that was provided at the time of writing this report. All the data presented here should be considered preliminary. The assortment and pricing were not determined yet, but it seems that the diameter is fixed to 60 cm but the lengths can be different - varying from 10 m to 20 m. The choice of sizes to be manufactured appears to significantly limit the system's applicability, though it may also reflect the gathered experience with the use of this system.

Certain issues may be critical for proper functioning of this system:

- The sliding stability depends on the friction between the soil and the plastic skirt. A higher level of retained water (greater diameter of the tube) may be achieved only by increasing the length of the skirt. In such cases, the critical factor becomes tensile (tearing) strength of the blanket material at the contact with the tube, which limits the height of retained water, i.e. the tube diameter. This may become an issue only if the manufacturer decides to increase the dimensions of the system.
- By the nature of its design, the NOAQ tube cannot be placed across a strong current. The producer claims that it can be placed in a shallow water running in the same direction as the axis length. This is not a disadvantage by itself, even though the manufacturers of water-filled tubular systems advertise this possibility as a particular feature of their products. Even so, after reading a manual for installation of a water-filled tube (for example, the GeoChem's "Water Structure", Appendix 2) it is hard to imagine the placement of such a tube in a wild stream which is common for flooding situations, especially those in Alberta.
- In fast flowing water the blanket may start fluttering and twisting. The manufacturer explains that the depth of water is a critical issue - shallow water does not provide enough pressure on the blanket and sufficient adhering to the ground. Some brick or stone may be needed here and there to keep the skirt in place in shallow flowing water along the tube. Since the water velocity normally increases with the depth of the current, possible fluttering of the skirt in deeper (and faster flowing) stream is prevented by increased vertical water pressure itself.
- The floating debris is extremely dangerous in the case of air-filled bladder - one puncture compromises the whole barrier.

In conclusion, the NOAQ system appears to be a very interesting idea, particularly in:

- sparsely settled areas - as a closure structure of individual objects, or smaller housing complexes, and
- remotely from flooding streams, in conditions of a slowly flowing water.

The use of presently available product is limited to lower water levels of up to 0.5 m.

4.5 Modular retaining wall systems

Modular retaining wall systems are hollow precast reinforced concrete wall sections that can be filled with soil and stacked in order to form a self-supporting wall. A typical example of this type of structure is shown in Figure 4.5.1, taken from Duncan *et al.* (1997).

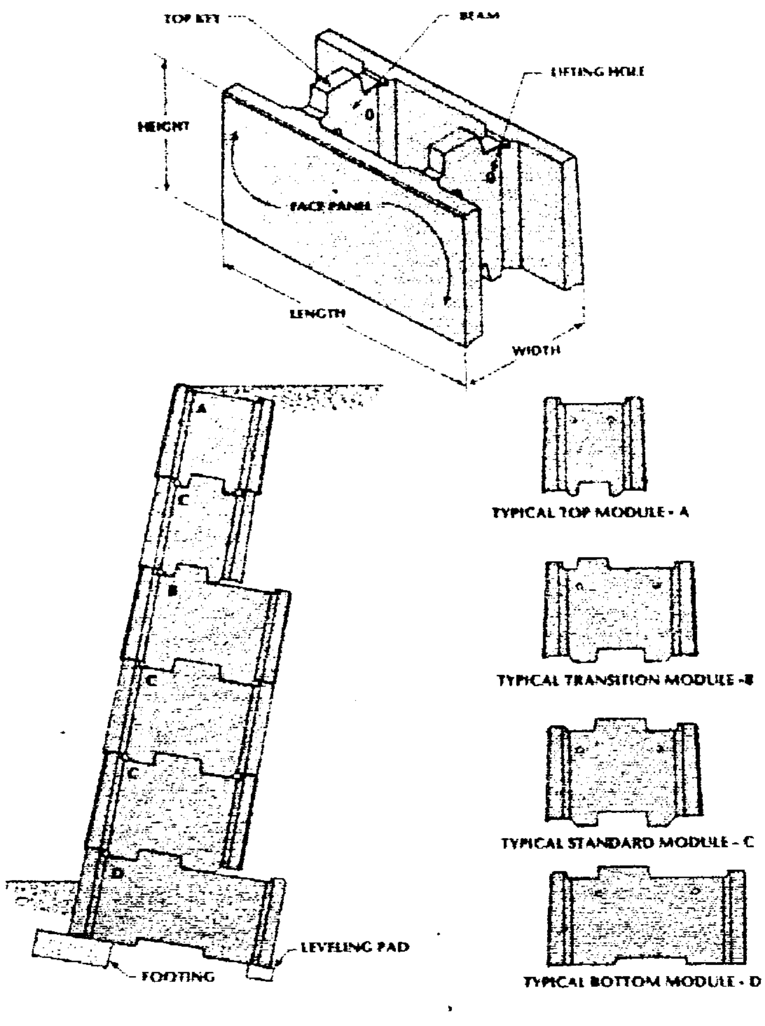


FIGURE 4.5.1 MODULAR RETAINING WALLS ("DOUBLEWAL")

A variety of modular components for construction of this type of wall, offered by different manufacturers, are commercially available at present. A limited list of the manufacturers is given in

Appendix 2. These structures have been used as permanent protection measures. Their use as temporary flood fighting structures can be sought only as a more efficient alternative to common sandbag walls.

The system is based on gravity action - its stability against sliding and overturning relies on the weight of concrete sections and the soil filler. Stability calculations can be done using formulas for gabions (Appendix 1, section A.7.1). Such an analysis is entirely dependent on the geometry of units.

Impermeability of the wall is achieved by sealing rubber pads placed along joints, or a membrane fabric that can be placed on the wet side of the wall, in similar manner as with Portadam (section 4.2.3). Seepage through the ground is determined in a usual way, by the average hydraulic gradient (Appendix 1).

This system is based on a proven concept. Heightening of the barrier is accomplished by stacking another row of elements on the top of the wall. Heavy equipment is required for installation (large crane). Fill compaction may be done using hand equipment. It seems that making corners (turns in horizontal plane) is relatively easy and safe, especially when lateral and corner elements are available. Preparatory works are needed where necessary: levelling the ground where foundation will be placed and placement of a concrete foundation. These works can not be conducted in the conditions of imminent flooding danger, so the system is mainly intended for use in urban conditions, or where foundation soil is of a good quality.

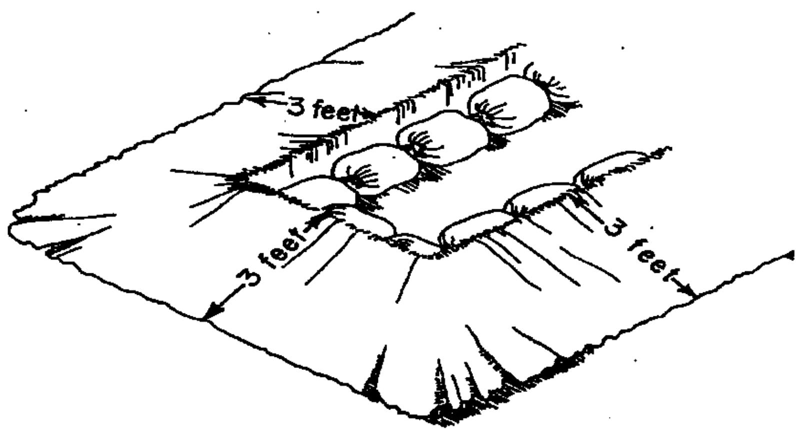
The installation procedure is not simple and requires trained or skilled manpower. It is also labour-intensive and time-consuming because of the preparatory works needed. The transport requires heavy trucks, even to small distances.

Initial cost is high if the system is to be purchased. It may be stored in the open air, but the storage space required may be critical. Another problem is with the storage locations - they should be close to the potential site of application. The system is reusable and there are no maintenance costs. Transportation and installation costs are high because of heavy equipment. There are also significant removal costs.

In conclusion, advantages and disadvantages of these systems are comparable to those of gabion-like structures, though the installation time will be greater and more skill is required. And the feasibility in flood protection is similar: modular retaining walls may be considered only as a more efficient replacement of sandbag walls, the only difference being that they appear more suited to urban conditions (and where the units and filler material are at hand), while gabions seem better for rural areas.

4.6 Fabric fold-back walls

These are actually reinforced earth structures. Two examples of such walls are shown in Figure 4.6.1 (Torrey and Davidson, 1994; Duncan *et al.* 1997). Essentially, a vertical reinforced earth wall is constructed using geomembrane sheets to encase and wrap each soil layer at the face of the slope. Sandy soil is preferred as a filler. To facilitate and improve the construction, wooden forms are used for filling a section of the layer. Alternatively, sandbags serve as lateral supports for each layer. Both techniques are shown in the figure.



Construction of Sandbag Reinforced Fabric Fold-Back Wall

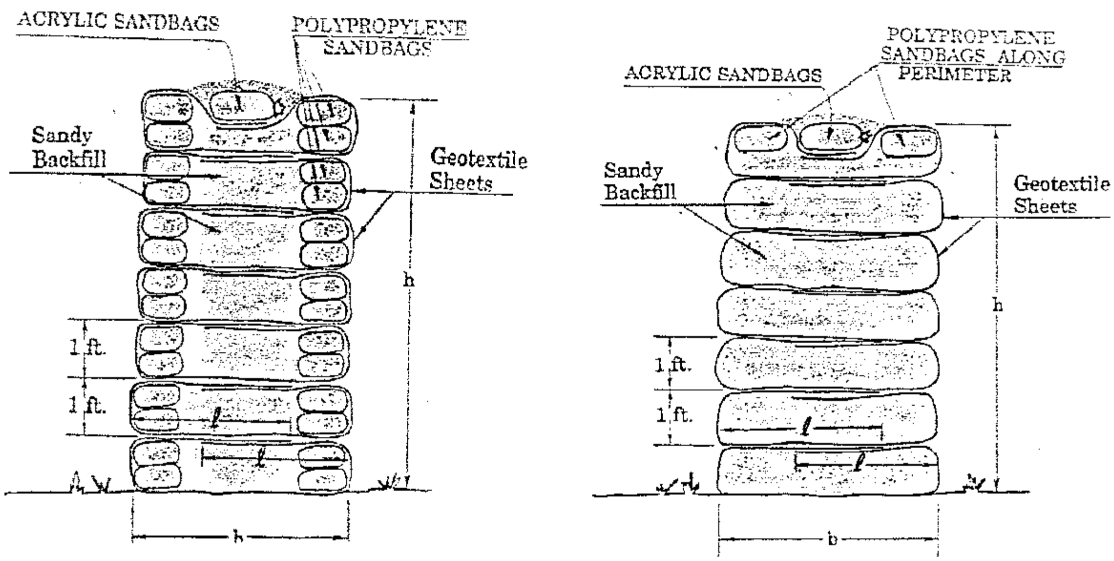


FIGURE 4.6.1 FABRIC FOLD-BACK WALLS

Stability against sliding and overturning can be calculated as for an ordinary gabion (Appendix 1, section A.7.1). The parameters for the base friction angle should conform to the values obtained for the soil-geosynthetics interface.

Seepage below the wall is characterized by the shortest possible seepage path and average hydraulic gradient (Appendix 1, section A.5). Seepage through the wall is dominantly determined by the permeability of the geosynthetics, especially in the case of sandy filler.

The structure is somewhat more complicated than a sandbag wall, but is more reliable if constructed properly. The method is labour intensive. The manpower should have specific skills and experience, although not much more than for sandbagging. There is no need for preparatory works.

The system accommodates to the terrain and may be made with varying heights. It is easy to increase the height if required during the flood.

The main advantage over sandbagging is in the ability to utilize machine filling to speed installation (a loader may be used), although this may impose certain limitations in case of saturated soft soils. Otherwise, the time needed for installation is comparable to that for a sandbag wall.

Initial investment for this method is roughly the same as for sandbag stockpiles, as well as the storage requirements. The system is for a single use and all the material should be considered consumable due to possible damage of geosynthetics sheeting by floating debris. The expenses for removal are roughly the same as for sandbags.

There is limited experience in its use as a flood fighting method.

It is our opinion that fabric fold-back walls may be considered essentially as a more efficient replacement of sandbag walls. There are probable benefits in shorter installation time (with machine construction), smaller footprint, greater possible heights (with the same volume of material) and more reliability in a statical sense, with the costs practically the same for both methods. However, when compared with gabion barriers, fabric fold-back walls seem inferior due to more labour needed and longer construction time.

5. RELEVANT ISSUES (OR EVALUATION CRITERIA)

5.1 Stability

5.1.1 FACTORS OF SAFETY AGAINST SLIDING AND OVERTURNING

Factors of safety against sliding and overturning, which are commonly used in assessing stability of a structure in geotechnics, were calculated following a simplified procedure described in Appendix 1. It is worth noting that this approach, and probably any other, more sophisticated method of stability calculation, is only a high idealization in the case of a temporary flood protection system. Such a structure is usually assembled without being previously designed, its geometry and structural properties are known "on average" from experimental verification or model tests, and the system is installed (or built) on terrain where the conditions and properties are not known in advance, but can only be estimated. Therefore, the values of safety factors should be generally very high. It is not possible to impose rigid limits - threshold values - for the factors of safety, due to uncertainty of possible conditions in use. They have to be considered in the complexity of all evaluation criteria.

The factor of safety against overturning cannot be calculated for certain systems. For example, in the case of a flexible structure such as water (or air) filled plastic tube, overturning action of flooding water merely converts to rolling deformation and resulting horizontal movement of the tube.

5.1.2 SEEPAGE

Flooding water can seep below and through the water barrier. This issue may be usually neglected with a properly constructed defence structure, since the amount of leaking water is then very small. The problem grows with the duration of high levels of retained water.

5.1.2.1 Seepage below the barrier

In this report, the resistance to seepage below a barrier is measured by the value of hydraulic gradient in the ground, using a simplified method described in Appendix 1. This is a standard procedure in geotechnical engineering for the earth structures that are continuously subjected to a difference in water levels on its sides. The underlying theory assumes full saturation of the soil, laminar flow, etc. It is questionable whether all these assumptions are valid in a specific situation. For example, the method in Appendix 1 assumes steady-state process in a saturated soil state. If the soil is unsaturated before the flooding event, certain time is needed to establish the assumed theoretical conditions. During that time interval the uplift pressure onto the structure will be lower than the calculated one and, consequently, the stability against sliding and overturning higher than the computation shows. Also, the amount of water leaking beneath the barrier will be less than the calculated discharge. In both cases, the average hydraulic gradient calculated is the upper limit of the possible range and the calculation itself is on the side of safety. Therefore, the hydraulic gradients calculated in Appendix 1 are only guidelines for differing among various systems.

It also must be noted that the consequences of seepage depend on the type of the ground: if the underlying ground is impermeable, intact rock, there is probably no danger at all; an opposite example is loose sandy or silty soil where the washing-out of fine particles is possible. In other words, a structural system is not the best possible defence line in all ground conditions - its feasibility should be assessed from the aspect of local circumstances.

Two specific problems are the condition of the contact between the structure and the ground, and the velocity of the flowing water.

The structure-soil interface is often the path of weakest resistance to leakage. Illustrative examples are: stone-filled gabions on an uneven, rocky surface; water-filled plastic tubes on mountain river bed with large angular boulders, etc. All possible structure / base combinations can not be predicted in advance, but may be overcome during installation. Every possible effort should be engaged in proper preparation of the ground surface: levelling (filling the holes, trimming the unevenness and “humps”); pulling-out the roots; removing fallen branches, stones, etc.

The above considerations are related to still or slowly flowing waters. However, the currents with high velocities may erode the bed or banks and cause undercutting along a portion or even the whole barrier. In the case of a stiff structure this leads to greatly increased leakage, washing-out of the soil material, appearance of gaps in the contact and, sometimes, to eventual loss of stability of the structure. On the other hand, flexible structures possess the property of “self-healing” in such a situation - they conform to the ground to provide an effective seal. Even when the ground is eroded after installation, they may fill the gaps to maintain the seal.

It should be pointed out that rigid structures, such as Richardson’s concrete and steel barriers or Portadam, seem particularly prone to seepage induced instabilities (due to short seepage paths and relatively high hydraulic gradients), while highly flexible systems, such as water-filled geomembranes, exhibit significant advantages over them with this regard.

5.1.2.2 Seepage through the barrier

Seepage through the structure is difficult to assess. It is affected by the type of structure, including:

- the number of segments, i.e. junctions, along the unit of length,
- the seaming at junctions (in the sense of designed solution, because its achievement may vary in practice, depending on local conditions and the skill of labourers),
- additional sealing measures - either designed and provided by manufacturer or invented and available at a specific site, etc.

It is also affected by the quality of construction, which can be widely varying and unpredictable, depending on:

- the terrain conditions: relief - flat, sloping, undulating, etc., surface - smooth or rough, soft or hard, etc.,
- the stiffness of the structure,
- the skill and experience of the construction teams, etc.

In principle, continuous structures did better in the evaluation than the segmented ones (for example, geomembrane tubes versus modular retaining walls and segmented concrete barriers); systems with a designed sealing layer (e.g. Richardson’s barrier with compression gaskets between elements) did better than those in which impermeability should be provided using locally available material (Jersey Highway Barriers wrapped with plastic sheeting), and so on.

5.1.3 INDUCED LOADING ON SOIL

The loading exerted on the structure base is not an issue for gravity (a dyke-like) structures, having a large continuous footprint area. Soil loading becomes important when considering the structures consisting of a panel with supporting legs, or of similar design (for example, Portadam or Richardson’s flood control barriers). The water pressure on the panel results in a high concentrated load at the foot of the supporting leg. This load, when applied to soft, compressible soil, produces settlement of the leg and corresponding deformation of the whole structure. Excessive deformation may, in turn, cause overstressing of certain structural members and, finally, destabilization of the structure as a whole. Particularly disadvantageous in this respect are considered:

- the position of the resultant force far from the centre of the contact area, and
- low inclination of the resultant force, i.e. a high horizontal component.

All the above mentioned obviously limits the range of applicability of such systems - they can not be considered feasible for soft grounds, water saturated soft clays, etc.

It has to be pointed out that the parameters describing the magnitude, position and orientation of the soil loading are not constants for a certain system - they depend on the height of the water to be retained, flowing velocity, conditions of the top soil, the shape of the structure (straight or broken line, with corners), and so on.

5.1.4 TYPE OF STRUCTURE

5.1.4.1 Ability to fix or strengthen the system in use

Linear structural systems are very vulnerable to damage and easily lose their function when any of their segments, or members, fails. Take as an example a conduit which gets clogged in only one cross section, or a road with a traffic jam or a landslide that occurs at a single spot along a route. The same mechanism is valid in the case of a flood protection system - if water bursts through at a single point the whole defence line breaks down. It is, therefore, very important to have a “flexible” system which, by its very concept and design, allows its efficient and fast repair or strengthening during a flood event. This also assumes some degree of “ductility” of the structure - one expects that a structural member will not collapse suddenly, but will give some signs of overloading (an excessive deformation or movement), which can enable the person in charge to undertake appropriate measures to repair it or support it in due time.

Considering this problem, it appears that sophisticated structural systems exhibit significant weaknesses in this respect. Their installation always requires specialized knowledge, heavy equipment, free access and longer response time, and these are usually lacking in a flooding situation. Therefore, simple systems like geosynthetic tubes filled with water, or gabions, are preferred when compared with the structures like concrete or steel barriers (Richardson’s systems, Portadam, Jersey barriers, etc.), fixed post-and-lagging systems (section 4.3) or modular retaining walls (section 4.5). It is difficult to imagine how one can replace Richardson’s concrete element, or support a Portadam segment with a deformed leg, under the conditions of water pressure on the panel, or fast flowing current with dynamic fluctuations of water pressure loading. In the case of gabions or plastic tubes it is intuitive and relatively simple (although not easy) to support the structure by an additional row of elements behind those which began to yield.

5.1.4.2 Adaptability to changing terrain conditions

This issue is related to flexibility in use of the available protection system. This question arises when one particular protection method must be able to cover large areas consisting of zones with different features, for example:

- both urban (densely populated) and rural (sparsely settled areas, with dwellings sited far from each other) settings,
- various relief (flat or undulating terrain, horizontal or sloping ground, etc.),
- different ground surfaces (rock or soil, smooth or rugged) and so on.

It is desirable, in such cases, to be able to apply the same defence method for a whole area. Such a decision is justified from both financial and organizational aspects. However, this does not nullify the use of a highly specialized protection structure for an individual object or specific conditions, when such a structure suits the purpose.

Considering terrain adaptability, simpler systems like gabions and plastic tubes are, again, favoured in comparison with more sophisticated structural systems (post-and-lagging, removable concrete barriers, etc.)

5.1.4.3 Assortment and modularity (variety of standard shapes and sizes)

This question is related to the adaptability requirements in section 5.1.4.1. It is desirable to operate with a structure that is equipped with various lateral (cross-sectional) dimensions, lengths, weights, etc., or in various standard units which can be connected together to form structures of varying geometry and structural characteristics. This enables an "optimization" of the defence to given circumstances.

This point can be illustrated by examples of :

- variable geometrical shapes of defence lines in the cases of a single house (nearly rectangular ring, with corners) or a dyke raising (straight or slightly curved),
- gullies in a generally flat area, where the protective line must have different heights, or may be curved to circumvent (depressions),
- rising water level in front of a constructed defence line, on which height has to be increased, etc.

It is emphasized that the capability to make corners in a protective structure, with the stability and functionality of the system preserved, is very important for smaller municipalities which may plan to defend only vital infrastructural objects or sites.

5.2 Constructability

5.2.1 TIME REQUIRED FOR INSTALLATION AND REMOVAL

This is, beyond a doubt, one of the crucial factors for evaluation of a temporary flood protection method. Only a net time of installation of a system is considered here - it is assumed that all the required material and equipment are available on site. This data is, actually, what is provided by the manufacturers in their promotional material.

The time needed for transportation should also be accounted for, but it is more an organisational than technical problem. It depends on the planning and organization in an individual municipality: awareness of imminent flood danger (previous experience, meteorological forecast, etc.), water level monitoring service upstream, locations of stockpiles, adequate stored quantities, available transportation vehicles, accessibility to the site, etc.

After discussion with officials in Peace River and Pincher Creek it was concluded that the response time in conditions of a flood alert is at least a day or two. Assuming that there is enough time for transport from a storage area to the site, and provided that the locations have been pre-determined, the time for installation should be roughly estimated to be from a few hours up to one day, or maximum two days. The ability of various systems to meet these time constraints depends on the length or area to be protected.

The time required for removal of the protective system can sometimes be a very significant factor, although the work itself occurs in more comfortable circumstances. For example, removal of the filling material and cleaning of the site in the case of a gabion wall is not comparable at all with the time needed to empty and roll a geosynthetics tube filled with water.

The data presented in this section are, as a rule, borrowed from commercial publications. It is noted when particular data is found in reference publications or official reports.

5.2.2 SIMPLICITY OF CONSTRUCTION

Field trips carried out in support of this research clearly indicated that a protection system should be as simple as possible. “The simpler, the better!” and “User-friendly systems are expected - the ‘user’ is an amateur!” is what was heard from the officials with experience in flood protection. This discourages all methods and structural systems, regardless of their efficiency and economy, which require specialized knowledge and experience in their assembling (i.e. requires an engineer or technician at the site) and favours simpler techniques and structures for which installation is intuitive, straightforward and consists of a few simple actions.

5.2.3 LABOUR REQUIRED

Available labour is another important criterion. Although there are not enough permanent employees in services involved in disaster mitigation and protection, there are generally enough volunteers and mobilized people in the case of emergency. Sometimes, problems may appear in sparsely populated rural areas, but generally the number of labourers is not an issue, although municipalities visited during the field trips asked for non-labour intensive methods. The difficulty lies in the fact that the manpower available includes individuals without relevant skills. This is closely connected with the requirement for the simplest possible structural system in the previous section - skilled personnel should not appear as a requirement.

5.2.4 EQUIPMENT FOR TRANSPORT AND INSTALLATION

Transportation vehicles and installation equipment are not an issue in urban areas, but they may not be available in small rural communities. Problems may thus arise with the systems which require some filling material - a loader is needed, or the structures which consist of heavy parts - lifting and manipulation equipments are necessary. Another major difficulty is also the accessibility for heavy equipment in rural areas and remote sites.

An ideal system is, therefore, a structure that is segmented so that pieces can be transported using small trucks and carried by hand, desirably by two people only, to remote places without man-made access.

The systems reviewed herein are considered in the context of which are suitable for application in cities, or where developed road network exists, and those which are better for rural areas or remote sites.

5.2.5 REQUIRED PREPARATION AND OPERATION SPACE ON SITE

On-site preparation should be reduced to a minimum because of usual lack of free space. In cities, the areas close to rivers are usually settled, and problems appear with access roads between houses and operation of construction equipment in yards. In villages, natural obstacles are trees, shrubs, uneven ground, etc.

An ideal system based on this criterion is, again, a segmented structure which can be placed without special requirements regarding the base ground (e.g. cutting roots, removing sharp stones, levelling, and similar) and assembled without any special equipment, i.e. using only hand tools or widespread available common equipment.

5.3 Costs associated with protective structures

5.3.1 INITIAL INVESTMENT (PURCHASE COST)

The expenses should be estimated in total, not separately. For example, a higher purchase cost may be connected with less expensive maintenance. Therefore, initial investment (purchase cost) is considered as just a part of the total cost of protection.

5.3.2 STORAGE

Storage requirements are a very important issue. The field trips have shown that there is not enough storage space in rural communities, especially sheltered or closed ones. Therefore, the protective systems which involve some type of inflation / deflation procedure are convenient because of smaller storage space needed.

Another alternative regarding the storage and stockpile locations was offered by the visited municipalities: to establish centralized stockpiles for larger areas, e.g. districts. The advantages are:

- more components of a chosen structure may be purchased for the same money,
- storage conditions are more controllable, resulting in increased lifetime of the system,
- more efficient operations - with adequate distribution, the protective system can be shared by many communities.

This, on the other hand, this requires certain organizational changes in the flood protection policies which are beyond the scope of this study.

The nature of storage space (open, closed, or only sheltered) is an additional factor considered. Sometimes, better storage conditions can increase the lifetime of a structure, reducing storage costs to some extent. Compare, for example, Jersey concrete elements, which can be left in the open air, with water-filled plastic tubes that deteriorate when exposed to extreme cold or to sunlight (ultraviolet rays).

5.3.3 DURABILITY IN USE AND VERSATILITY

Durability in use is a twofold issue:

- firstly, whether a system is designed for a single use or as a multiple-use structure, and
- secondly, what is the degree of survival of its members and parts in normal use.

The first point seems clear: water-filled geomembrane tubes, removable concrete barriers and similar systems are intended for multiple use, as opposed to fabric fold back walls and sandbags which are single-use systems. It appears, however, that this natural division is too rigid for certain systems.

Take, for example, cellular (gabion-like) barriers, described in section 4.1. They are primarily permanent protection systems. When used for temporary protection, the owner naturally wishes to save as much material as possible. Multi-cellular metal cages can be emptied by careful lifting on one side, disassemble, cleaning and then storage. However, the cages may be deformed so much that they can not be used again. The percentage of wasted cages depends on their size (larger units deform more than the smaller ones), their position (if cages are stacked one over another, those which were in bottom rows are, on average, much more deformed than those in top rows), the nature of filling material, etc. There is additional expense of removing old, torn and worn geosynthetic sheets which served as an impermeable lining of the cages, etc. The reusability, thus, becomes more an economic than a technical problem, since the cost for repair may closely approach the cost of purchase of a new structure.

Another illustration of problems with versatility in use may be imagined with water-filled plastic tubes. They are usually advertised as versatile systems which, when not in primary function, may be used for storing another liquid (by making a pool where that liquid is poured) or for storing drinking water by filling the tubes themselves. The problem with versatility is that the primary function or use of a system often limits its adaptability. If the geomembrane tubes were used in flood protection - filled with flooding water, they can not be used for storing drinking water any more (unless completely cleaned and disinfected), and so on.

The survival of parts of a protection system depends on many factors: design, conditions of application, possibilities of repair, etc. Taking as an example inflatable plastic tubes (section 4.4), they are vulnerable to puncture by sharp debris, flowing trees, etc. carried by stormwater. The protection is often a special outer coating tube, made of rugged reinforced plastic, or the material of the tube itself is strengthened against rupture by adding ceramic chips, or wrapped in reinforcing geogrid. Nevertheless, it may happen that a tube is damaged during a flood. It may be then repaired simply by gluing it (the manufacturers usually provide such maintenance kits, or by specialized manufacturer's process in case of heavy damage. As explained in previous paragraph, the maintenance is an economic problem. Technical details, such as the percentage of reusable units, can only serve as guidelines for financing. Unfortunately, there is no such data in available materials, mainly because of insufficient experience with the systems advertised. Therefore, conclusions on durability of considered protection methods, which are described in this report, are based exclusively on a general previous knowledge of the behaviour of similar structures and materials.

Versatility is a desirable feature - if the system can be used for other purposes (rented to other users) then it may (partly) repay itself. The manufacturers usually emphasize this option, although one has to be cautious when considering this as an advantage - primary uses of the system often limit future ones, as explained in previous paragraph of this section.

5.3.4 INSTALLATION AND REMOVAL COSTS

Installation costs depend on the requirements of specialized equipment and tools, as explained in sections 5.2.4 and 5.2.5. Simpler methods, which involve only extensive manual work, are usually considered much cheaper because the labour is free – the manpower in flood protection consists of volunteers. The methods which assume the use of heavy equipment and skilled professional manpower are sometimes not desired because of high rates of heavy machinery renting (or purchase costs), but this may be a false economy, resulting in unnecessary prolonged installation times and lower quality of a protection barrier.

Removal expenses should not be forgotten in calculating the total cost for single-use systems. They sometimes contribute up to almost 50 %, as the example of sandbags shows.

5.3.5 STAFF TRAINING AND SUPERVISION BY MANUFACTURER

The expenses for training personnel with manufacturer's supervision during trial construction of the supplied protection structure are commonly included in the purchase price. Sometimes, they are offered free of charge, as incentives. Of course, those methods which do not assume technical education (engineering professions) or special skills are rated better than others.

6. SELECTED SYSTEMS

The following systems were chosen to be recommended for further experimental or practical testing and verification. The selection is not based on any rating system, but on engineering judgement of overall utility, based on criteria described in the previous section.

6.1 Inflatable (water-filled or air-filled) tubular geomembranes

The strongest points that recommended these relatively new systems are the fastest installation and lowest requirements for labour and professional skills. These very simple statical systems show excellent behaviour with respect to stability and seepage criteria (Table 6.1). They are particularly easily adaptable to uneven ground. Storage space is small and the requirements regarding storage (temperature, sunlight and humidity) are modest. These systems can be easily transported by common light vehicles and can be carried by hand (except the heavy systems for high water levels). They are reusable and can be simply fixed (holes patched) even in use, on site.

The weakest points are high initial cost for purchase and questionable durability against floating debris carried by water current. Due to high flexibility and tendency to rolling, there may be anchorage problems in the case of flowing water and wave action. Also, huge amounts of water needed for the water-filled systems may pose certain limitations on their use – i.e., they need to be located close to streams and ponds. The same is valid for use during low temperatures because of freezing in water-filled systems.

The area of possible application of these systems is probably the widest of all the methods discussed. They can be used both in urban and rural conditions (regarding the ground requirements and available space at the surface). They are very good as closure structures for individual objects, but also can be applied to confine streams, quickly adding an extra height on existing levees (taking care of the floating debris problem). These systems can not be utilized in situations where ice cover on the water bodies exert high forces on lateral dykes. The height of retained head, quoted as the relevant experience by the manufacturers, is up to 1 – 1.5 m in slowly flowing water. Structures for water heights of up to 3 m are available.

It seems that the Water Wall system is somewhat inferior to the others (section 4.4). The Clement system had surprisingly low calculated stability parameters. This is further addressed in the addendum.

The NOAQ system (see page 72) should be particularly noted for the best overall analytical stability parameters and attractive concept. The system merits further attention and development.

6.2 Cellular (gabion-like) structures

Cellular structures are considered complementary protection technologies for inflatable plastic tubes. As noted earlier, they were considered a more efficient replacement for sandbag walls. Their main advantages are robustness, low cost and speed of installation (when machine filling is possible). The cellular wall is resistant to floating debris impacts and wave action, and low temperatures as well. Also, a very strong point is that there are no special requirements for storage and the space needed for storing is very small (collapsible structures). The metal cages themselves can be transported using ordinary trucks and can be carried by hand. The cages may be considered to be partly reusable, depending on the conditions of use and resulting deformation.

The main disadvantage is the need for removal and cleaning after the use and large costs associated with that. The need for heavy equipment to speed the construction raises the question of site accessibility - cellular structures are not suitable for places where soft saturated clays are the foundation soil, unless they are filled manually. The fill material also poses specific limitation: although any material may be used, it seems that sandy soils are preferable (better workability). On the other hand, large hydraulic gradients beneath the structure (Table A.1.3) may become a problem under prolonged exposure to flooding water due to the possibility of soil erosion, particularly in looser silty and sandy soils.

Cellular structures seem particularly appropriate for stream diversion and confinement (dyke raising) situations, due to the robust design. Stacked, multilevel barriers with great widths of the cross section may serve as good gate closure structures. The retained head is about 1 m for single row of gabions, and up to 2 – 3 m for stacked barriers.

According to available information, there are practically no technical differences between the two types of gabions available: Hesco “Concertainer” and Maccaferri “Flex Mac”.

6.3 Fixed post-and-lagging system

The only commercially available system in this class is the DPS 2000 system, manufactured by GOH, Germany. Although the GOH system is advertised as convenient in a general flooding situation and any site conditions, it is more likely that this type of structures should be custom designed for any particular application.

The GOH system is the most reliable protection system with respect to stability aspects, assuming that the host structure on which it is installed is solid enough. This system enables the greatest heights of retained water: up to 4 m, with the use of leaned props on permanent foundations. The sealing is almost perfect and the installation is fast and easy. The height of the structure may be gradually adjusted to the water level. The structure is completely reusable, has long lifetime and is very durable in use. Installation costs are very low. The only problem may be seepage through the ground in case of inadequate host structure - for example, a thin shallow wall.

The overwhelming disadvantage of this structure is its cost, probably the highest of all the systems discussed. The initial investment (purchase price) is extremely high because of expensive materials. The storage space must be secured against theft. Preparatory works are necessary, and may be time-consuming and costly if strengthening of the host structure is required.

The GOH structure is, in our opinion, a single use system: it is probably the best closure structure for important single objects in urban conditions, for those companies which can afford the cost of this protection. Although the primary use of this system was for stream confinement, as a hidden levee along the rivers in European towns, it is questionable whether such a use may be economically justified in comparatively more sparsely populated Canadian areas, with extremely long defence lines.

6.4 Jersey highway barriers

The only system from the group of concrete removable structures that is recommended is Jersey highway barriers. It was mostly because of their wide availability across the country, since the calculated stability parameters were not particularly good, and the rating with regard to other criteria was comparatively modest.

The good points of Jersey barriers are simplicity and fast installation, if heavy construction equipment and the units are available on site. Also, the cost is very low: there is no initial (purchase) investment and no need for storing space. Also, there is its durability in use: there are no damages and no maintenance expenses.

There are many disadvantages that limit the applicability of Jersey barriers. The site accessibility for heavy equipment limits its use in rural areas and places with soft soils in the foundation. It is difficult to make corners - a broken line in plan - with these units (sandbag plug is needed to fill the corner slot), therefore they are not convenient as closure structures. The stability and seepage problems with this system are likely to be remedied with the use of plastic wrapping as an impermeable blanket, as suggested in section A.7.2. Dangerous conditions seem to be when there is wave action of floodwater.

The primary use of Jersey highway barriers in flood control is seen as levee raising means in spatially limited areas: in urban conditions or where the units are available and the road network is developed, because of site accessibility requirements. Their use is best suited for flat, stiff terrain and for long straight defence lines. The maximum height of retained water is 0.5 metres. Stacked barriers, which allow water heads up to 1.5 m, seem too vulnerable in real circumstances and are suspicious from stability aspects.

6.5 Comparative data

Table 6.5.1 presents stability factors and the costs to make a barrier about 30 m (100 feet) long, which is to hold back floodwater of about 1 m in height, using various selected systems described in sections 6.1 to 6.4. The gathered data are not homogeneous (see Remarks). The costs shown are not fixed, but will depend on actual, given circumstances. The data used are borrowed from commercial brochures and should be taken cautiously. Stability factors were calculated using the friction coefficient $\tan \delta = 0.45$, i.e. the friction angle $\delta \approx 24^{o}$, and the unit weight of fill for the gabion-like structures $\gamma_{fill} = 18$ kN/m^2.

Type or commercial name	Length L	Width W	Height H	Maximum height of retained water H_w	Weight (empty)	Sliding stability F_s	Overturning stability F_o	Average hydraulic gradient i	Loading on soil q (kPa)	Price	Remarks
	(m)	(m)	(m)	(m)	(kg)						
Hesco Concertainer											
Mil 3B	30.5	1	1	0.80	630	2.0	2.6	0.8	18	$1,600	+ filling
Mil 4B	30.5	1.5	1	0.80		2.9	3.0	0.5	17	$2,400	Data used: γ_{fill} = 18 kN/m^2
Mil 9B	30.5	0.76	1	0.80		1.5	2.2	1.1	20	$1,600	tan δ = 0.45 (δ = 24^o)
Maccaferri Flex Mac											
	30.5	1	1	0.8	289	2.0	2.6	0.8	18	$ 2,100	+ filling
Aqua - Barrier											
Single Baffle	30.5	3.2	1.22	0.91	227	2.9		0.3	11	$6,400	Prices in US $.
Double Baffle	30.5	3.2	1.22	0.91	303	2.9		0.3	11	$6,800	
Aqua Dam											
AD04	30.5	3.6	1.2	0.96		2.5		0.3		$5,200	
Water Structures											
WSU 48-105	30.5	3.05	1.22	0.91	182	2.4		0.3	10	$3,900	Prices in US $.
Clement											
3 levels	30.5			0.91	245	0.7		0.9	24	$6000 - $9000	A single tube weighs only 20 kg.
GOH											
DPS 2000	30.5		1	0.8						$25,000	+ foundations. Prices in US $ (Duncan et al. 1997).

TABLE 6.5.1 COMPARATIVE DATA FOR VARIOUS SYSTEMS – RETAINED HEAD OF WATER IS ABOUT 1.0 M, APPROXIMATE LENGTH 30 M

7. CONCLUDING REMARKS

7.1 Summary comments

- There is no currently available “ideal” flood protection system which is applicable in all possible circumstances and organizational and working conditions. The best system in a given situation is the one which is at hand, can be properly constructed for the time available, and is capable of fixing and strengthening on site, if needed.
- The selected systems in section 6 are complementary: they are particularly suited for certain tasks and conditions, but should not necessarily behave equally well in a different environment. The flood control measures must not be applied blindly, without thorough analysis of actual local conditions in a protected area. In many situations only a combination of discussed methods of protection can give optimal results. Proper planning and preparation is needed for even the simplest methods to achieve full efficacy.
- The inflatable tubular geosynthetic systems are the type of protection structure which seemingly has the widest application: they can be used in both urban and rural conditions; there are almost no restrictions regarding the relief and underlying soil; they are easy to transport and the simplest and fastest to install. They appear particularly suited for closure structures in still or slowly flowing floodwater conditions, for retained height of up to 1.5 metres. The unfavourable conditions are: the currents which carry a lot of floating debris, fallen trees, etc.; ice jams which exert high lateral pressures; and possibly freezing temperatures.
- Cellular (gabion-like) structures are adequate protection for severe conditions, where inflatable plastic tubes cease to be advantageous. Cellular structures are particularly appropriate for: stream confinement and diversions; the currents with sharp and dangerous floating debris; and the extreme cold conditions. The head of retained water is usually about 1 metre. For higher heads of up to about 3 metres, very heavy equipment and construction skills are necessary.
- The post-and-lagging system is narrowly limited in flood protection: it is best as a closure structure for specified individual objects in urban conditions. Because of its high cost, it is intended for very important, vital objects and wealthy users. The height of retained floodwater is up to 4 metres, with proper supporting.
- Jersey highway barriers may be a satisfactory choice for a levee raising provided that the following conditions are satisfied: the barriers are available in the area, e.g. in urban conditions; the site accessibility is very good; the maximum head of floodwater is about 0.5 metres. Their use is best suited for flat, stiff terrain and for long straight defence lines.
- Centralized stockpiles for larger areas and wider co-operation among interested municipalities with similar flooding problems are certainly needed to achieve successful management and the cost-effectiveness of purchased protection systems. These are issues of wider social and political interests which are beyond the scope of this study.
- The data, which served as a basis for this report, are mostly from commercial sources. They are usually nonhomogeneous, reflecting different approaches and interests of their manufacturers and distributors. Also, certain information was lacking or unavailable. Therefore, it is recommended to verify, by experimental testing or field application, the vital properties of the flood protection systems considered in this report. This is particularly important for the option of centralized stockpiles, shared by many communities, which involves huge investments and probable organizational changes for adequate storage and management.

7.2 Recommendations for experimental verification and field testing

The verification testing methodology proposed in this section is not intended to be exhaustive or to deal with all the structures available. It is limited to the types selected in Section 6 and the structures which are representative for each type.

Testing of real structures in operational conditions is desirable, because of the complexity of the problem and numerous influencing factors. For example, difficulties may arise with model scaling and similarity relations). Co-operation by the manufacturers and distributors should be expected in providing free "sample units" for experiments, and by offering accessibility to the results of their own tests.

In principle, the tests should be performed in the conditions of both:

- non-flowing - still water, with controlled raising of levels to assess the seepage and stability (sliding) behaviour;
- flowing water with controlled discharge, and possibly with the wave action, to determine the stability parameters in such conditions.

In the latter case, the structures should be tested at various orientations with respect to the stream: parallel and oblique (with a few defined angles) to the current. It is also desirable to have different types of the underlying soil in the test process.

During the construction process, installation times and requirements for transportation and installation equipment should be checked.

Particular tasks for water-filled tubes may entail: supporting to prevent rolling, the resistance to puncture and capabilities of fixing the holes on site; etc. It is especially recommended to thoroughly investigate the behaviour of the Clement system which had low calculated stability parameters and very high seepage gradients beneath the structure, but otherwise posses certain advantages regarding construction and operation.

For the NOAQ system, the functioning of the drainage layer for different soil conditions should be investigated because it is essential for the structure's stability.

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APPENDIX 1: STABILITY ANALYSES

A.1 Notation

The following symbols are used in this Appendix (see Figure A.1.1 for graphical illustration):

B	base width of the retaining structure
L	length of the impermeable blanket
H	height of the retaining structure
H_w	height of the retained water
W	total weight of the structure (may include the vertical water pressure, acting downward, if the wet face of the structure is not vertical)
p_w	maximum water pressure at the base of the structure
F_w^h	horizontal force on the structure due to the pressure of retained water
F_w^v	vertical uplift force on the structure due to the pressure of retained water
N'	vertical effective force on the base of the structure ($N' = W - F_w^v$)
q	maximum induced distributed loading on the base soil
x	width of the active area of the base, in calculating the soil loading after Meyerhof
$r_{N'}$	lever of the N' force with respect to the downstream toe of the structure
r_W	lever of the W force with respect to the downstream toe of the structure
F_s	factor of safety against sliding
F_o	factor of safety against overturning
i	average hydraulic gradient for the seepage through the soil beneath the structure
l	the shortest seepage path through the soil below the structure
f	angle of friction of the base soil
d	angle of friction of the soil / structure interface
g_w	unit weight of the water
g	average unit weight of the structure

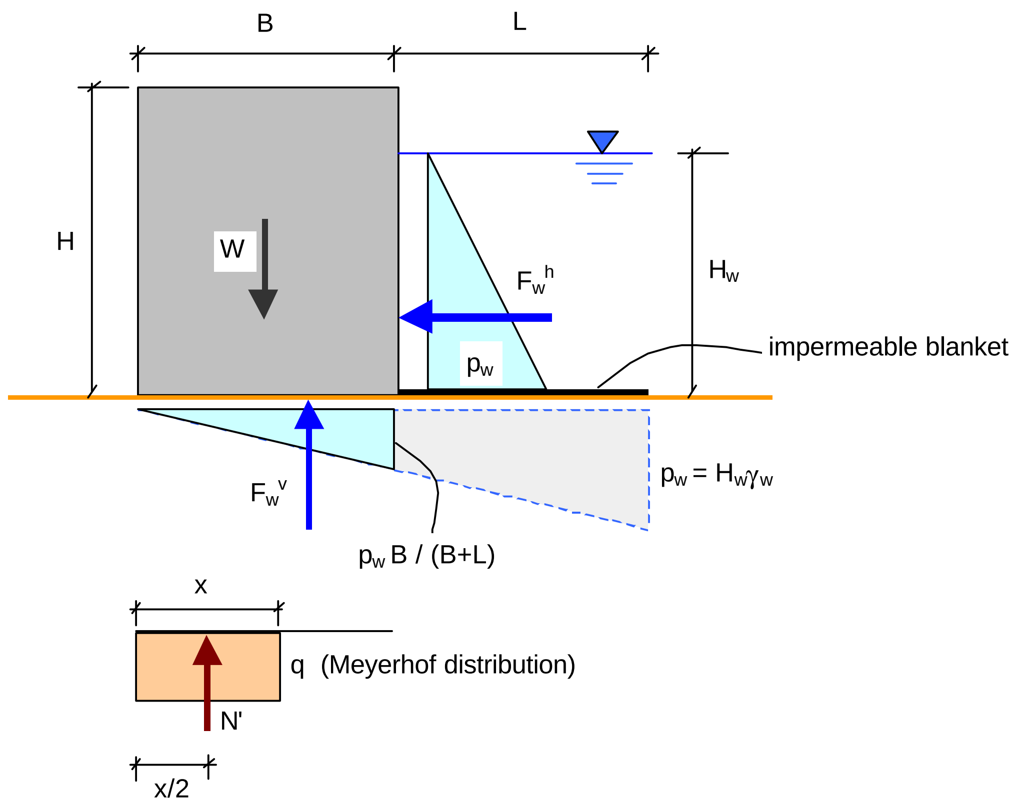

FIGURE A.1.1 STATICAL SCHEME FOR STABILITY ANALYSES

A.2 Assumptions

The following assumptions are made in the stability analyses presented in this appendix.

- The shear resistance of the base soil is entirely frictional - its cohesion intercept is zero. This is an approximation on the side of safety. The same is assumed for the shear strength of the structure - soil interface.
- The uplift force beneath the structure is linearly distributed. This means that the validity of the seepage theory for porous media is assumed and that there is no crack of finite width in the soil-structure interface.
- The impermeable blanket does not contribute to the sliding resistance of the structure. This assumption is justified for all those systems which design does not consider the blanket as a statically active member of the structure (the blanket is merely attached to the structure and the junction is not calculated to bear any stress). The only exception to this assumption is the NOAQ system which is designed in such a way that its sliding stability relies entirely on the frictional resistance of the blanket-soil contact.
- The height of retained water is, as a rule, assumed to be about 80 % of the total height of the structure: H_w » $0.8\ H$.
- Meyerhof distribution of induced loading on the foundation soil is assumed (Figure A.1.1). This is a simplification for numerical purposes. The normal force is assumed equally distributed over an area which size is determined from the moment equilibrium equation. The normal force acts in the centre of this area.
- The unit weight of concrete is assumed 24 kN/m^3. The unit weight of water is assumed 10 kN/m^3. The unit weight of filling material (e.g. for gabions) is assumed 18 kN/m^3.

A.3 Factor of safety against sliding

The maximum water pressure, acting at the base of the structure, is calculated as:

$$p_w = H_w g_w$$

The horizontal force of the water acting on the structure is determined as:

$$F_w^h = \tfrac{1}{2} p_w H_w = \tfrac{1}{2} g_w H_w^2$$

The vertical uplift force of the retained water acting on the structure is:

$$F_w^v = \tfrac{1}{2} p_w \frac{B}{B+L} B = \tfrac{1}{2} g_w H_w \frac{B^2}{B+L}$$

Total normal effective force on the base of the structure:

$$N' = W - F_w^v$$

Expressing the factor of safety against sliding in terms of the total forces on the base:

$$F_s = \frac{N' \tan d}{T}$$

and substituting N' and $T = F_w^h$, we obtain:

$$F_s = \frac{\left(W - F_w^v\right)\tan d}{\tfrac{1}{2} g_w H_w^2}$$

Note for water-filled geomembrane tubes:

The manufacturers of these systems, as a rule, do not provide the factors of safety against sliding for their products, nor do they provide the data and expressions for such calculations. This is, strictly speaking, a very complex problem in the statical sense because of the flexibility of the tube. The shape of the tube under internal fluid pressure is an axially symmetric figure which can be computed (Leshchinsky *et al.* 1997). Under the action of horizontal water pressure the form of the tube becomes completely irregular and very difficult to compute. An approximate method which assumes symmetric shape from the previous step and takes into account only horizontal component of water pressure may be used to calculate the stability against sliding.

The manufacturer of “Water Structures” describes in his brochure methods for sliding and overturning stability calculations, and provides tables with appropriate factors of safety for standard shapes of its members. Although the formula for the factor of safety against sliding is not correct, the values shown in the tables are good. However, both the method and the calculated factors of safety against overturning appear to be invalid because the uplift pressure due to the seepage underneath the tube was forgotten in the analysis. Also, it was mentioned elsewhere in this text that the factor of safety against overturning is not a valid number for highly flexible structures like these.

A.4 Factor of safety against overturning

This is easily obtained by expressing the moment equilibrium with respect to the downstream toe of the structure:

$$F_o = \frac{W\, r_W}{F_w^h \dfrac{H_w}{3} + F_w^v \tfrac{2}{3} B}$$

or, substituting for the moments of $F_w{}^h$ and $F_w{}^v$:

$$F_o = \frac{W\, r_W}{\tfrac{1}{6} g_w H_w^3 + \tfrac{1}{3} g_w H_w \dfrac{B^3}{B+L}}$$

In the case of a symmetrical structure $r_W = B/2$. Assuming the rectangular cross-section, as shown in Figure A.1.1, the weight is $W = BHg$, so that the above expression can be simplified to:

$$F_o = \frac{\tfrac{1}{2} B^2 H g}{\tfrac{1}{6} g_w H_w^3 + \tfrac{1}{3} g_w H_w \dfrac{B^3}{B+L}} = \frac{3 \dfrac{H}{H_w} \dfrac{g}{g_w}}{\left(\dfrac{H_w}{B}\right)^2 + 2 \dfrac{B}{B+L}}$$

A.5 Average hydraulic gradient beneath the structure

Assuming an ideal - impermeable blanket, and a perfect soil-structure interface, we obtain:

$$i = \frac{\Delta h}{l} = \frac{H_w}{B+L}$$

A.6 Induced loading on the soil

Meyerhof pressure distribution is used to approximate the loading exerted on the soil in the base of the retaining structure. The effective normal force *N’* is distributed equally over the area of width *x*, as shown in Figure A.1.1:

$$q = \frac{N'}{x} = \frac{W - F_w^v}{x} = \frac{W - \tfrac{1}{2} g_w H_w \dfrac{B^2}{B+L}}{x}$$

The width of active area *x* is calculated considering moment equilibrium around the downstream toe of the structure base:

$$N' \frac{x}{2} = W r_W - F_w^h \frac{H_w}{3} - F_w^v \cdot \tfrac{2}{3} B$$

$$x = 2 \frac{W r_W - F_w^h \dfrac{H_w}{3} - F_w^v \cdot \tfrac{2}{3} B}{N'}$$

Substituting for the forces, we obtain the expression:

$$x = 2 \frac{W r_W - \tfrac{1}{6} g_w H_w^3 - \tfrac{1}{3} g_w H_w \dfrac{B^3}{B+L}}{W - \tfrac{1}{2} g_w H_w \dfrac{B^2}{B+L}}$$

In the case of a symmetrical structure $r_W = B/2$. Assuming the rectangular cross-section, as shown in Figure A.1.1, the weight is $W = BHg$, so that the above expression can be simplified to:

$$x = \frac{B^2 H g - \tfrac{1}{3} g_w H_w^3 - \tfrac{2}{3} g_w H_w \dfrac{B^3}{B+L}}{BHg - \tfrac{1}{2} g_w H_w \dfrac{B^2}{B+L}}$$

A.7 Example calculations

For comparative purposes, stability calculations were made only for selected systems in section 6. The input data used were not completely reliable; missing or imprecise data were assessed where necessary.

A.7.1 GABION-LIKE STRUCTURES

These structures do not use an impermeable blanket on the wet side (Figure A.1.1). Substituting $L = 0$ into the equation for vertical water pressure F_w^v derived in section A.3, it can be simplified to:

$$F_w^v = \tfrac{1}{2} g_w H_w \frac{B^2}{B+L} = \tfrac{1}{2} g_w H_w B$$

The equation for the factor of safety against sliding then becomes:

$$F_s = \frac{\left(W - F_w^v\right)\tan d}{F_w^h} = \frac{\left(BHg - \tfrac{1}{2} g_w H_w B\right)\tan d}{\tfrac{1}{2} g_w H_w^2} = \frac{B\left(2\dfrac{H}{H_w}\dfrac{g}{g_w} - 1\right)\tan d}{H_w}$$

Since the friction angle of the soil-structure interface d is not known in advance, it was found plausible to reverse the calculation: the values of d were calculated assuming factors of safety F_s equal to the values 1.0 and 1.5. The equation used was:

$$\tan d = \frac{F_s H_w}{B\left(2\dfrac{H}{H_w}\dfrac{g}{g_w} - 1\right)}$$

The results are shown in Table A.1.1. The values of d corresponding to $F_s = 1.0$ (the verge of stability) depend on the shape and size of the cross-section, but generally vary between 12^0 and 17^0. This range may be considered acceptable for most soils, even in the saturated and softened state. The values of d corresponding to $F_s = 1.5$ (assessed as a reasonable stability level), vary between 18^0 and 25^0.

Speaking strictly in the sense of calculation methodology described in section A.3, friction angle d characterizes shear resistance of the structure-foundation interface, i.e. a sliding between two rigid bodies is assumed in derivation. The actual failure surface may deviate from the interface and pass through the soil (more likely) or the structure itself, depending on their relative strengths and the geometry of the problem. Table A.1.2 provides approximate ranges of variation of d angle for various soil types and soil-structure interfaces. It may be used as a rough guideline for selection of the proper protection structure for given natural conditions. When several cases from the table are pertinent in an actual situation, choosing the lowest possible value of d angle is on the side of safety. On the other hand, it should be kept in mind that the calculation in section A.3 is based on the assumptions from section A.2. Possible departures from these idealized conditions, unavoidable in reality, may lead both to decrease or increase of calculated sliding stability.

						$F_s = 1$		$F_s = 1.5$	
Type or commercial name	Wall height H (m)	Water height H_w (m)	Base width B (m)	Weight filled W (kN/m)	$\gamma H / \gamma_w H_w$	tan δ	δ (°)	tan δ	δ (°)
Hesco Concertainer									
Mil 1B	1.37	1.10	1.1	26.1	2.3	0.288	16.1	0.432	23.4
Mil 2B	0.61	0.49	0.6	6.7	2.3	0.223	12.6	0.335	18.5
Mil 3B	1	0.80	1	18.0	2.3	0.223	12.6	0.335	18.5
Mil 4B	1	0.80	1.5	27.0	2.3	0.149	8.5	0.223	12.6
Mil 5B	0.61	0.49	0.61	6.7	2.3	0.223	12.6	0.335	18.5
Mil 6B	0.61	0.49	0.61	6.7	2.3	0.223	12.6	0.335	18.5
Mil 7B	2.21	1.77	2.13	84.7	2.3	0.231	13.0	0.347	19.1
Mil 8B	1.37	1.10	1.22	30.1	2.3	0.250	14.1	0.376	20.6
Mil 9B	1	0.80	0.76	13.7	2.3	0.293	16.4	0.440	23.8
Mil 10B	2.12	1.70	1.52	58.0	2.3	0.311	17.3	0.467	25.0
Maccaferri Flex Mac									
	0.5	0.40	0.5	4.5	2.3	0.223	12.6	0.335	18.5
	0.5	0.40	1.0	9.0	2.3	0.112	6.4	0.167	9.5
	1	0.80	1.0	18.0	2.3	0.223	12.6	0.335	18.5
	1.4	1.12	1.0	25.2	2.3	0.312	17.3	0.468	25.1

TABLE A.1.1 SLIDING STABILITY FOR GABION-LIKE STRUCTURES

Classification	Friction angles (°)
Sands	
uniform fine to medium	26 - 30
well-graded	30 - 34
with gravel	32 - 36
Clayey soils	
very soft, saturated	12 - 18
highly plastic clay	16 - 22
silty clay	20 - 30
Interfaces	
concrete - sand	26 - 30
concrete - clay	12 - 18

TABLE A.1.2 TYPICAL VALUES OF FRICTION ANGLE d FOR VARIOUS SOIL AND INTERFACES

The expression for the factor of safety against overturning, calculated in section A.4, may be simplified substituting again $L = 0$, to obtain:

$$F_o = \frac{3\frac{H}{H_w}\frac{g}{g_w}}{\left(\frac{H_w}{B}\right)^2 + 2}$$

The results are shown in Table A.1.3. The factor of safety against overturning F_o varies between 2.1 and 3.0 which is considered satisfactory.

The values of average hydraulic gradient beneath the structure are computed using simple formula:

$$i = \frac{H_w}{B} \approx \frac{0.8H}{B}$$

and the results are shown in the same table A.1.3. The range of variation is from 0.8 to 1.1. As it will be seen later, these values are much higher than the average hydraulic gradients for water-filled plastic tubes, which are consistently about 0.3 - 0.4. It should be also kept in mind that, in saturated soils under prolonged exposure to flooding water, hydraulic gradients close to 1.0 may generate failure due to washing out of soil beneath the structure. In unsaturated soils with low permeability these gradients may be acceptable for short-term exposure.

Type or commercial name	Wall height H (m)	Water height H_w (m)	Base width B (m)	Weight filled W (kN/m)	γH / $\gamma_w H_w$	$(H_w / B)^2$	F_o	Average hydraulic gradient
Hesco Concertainer								
Mil 1B	1.37	1.10	1.1	26.1	2.3	1.07	2.2	1.0
Mil 2B	0.61	0.49	0.6	6.7	2.3	0.64	2.6	0.8
Mil 3B	1	0.80	1	18.0	2.3	0.64	2.6	0.8
Mil 4B	1	0.80	1.5	27.0	2.3	0.28	3.0	0.5
Mil 5B	0.61	0.49	0.61	6.7	2.3	0.64	2.6	0.8
Mil 6B	0.61	0.49	0.61	6.7	2.3	0.64	2.6	0.8
Mil 7B	2.21	1.77	2.13	84.7	2.3	0.69	2.6	0.8
Mil 8B	1.37	1.10	1.22	30.1	2.3	0.81	2.5	0.9
Mil 9B	1	0.80	0.76	13.7	2.3	1.11	2.2	1.1
Mil 10B	2.12	1.70	1.52	58.0	2.3	1.24	2.1	1.1
Maccaferri Flex Mac								
	0.5	0.40	0.5	4.5	2.3	0.64	2.6	0.8
	0.5	0.40	1.0	9.0	2.3	0.16	3.2	0.4
	1.0	0.80	1.0	18.0	2.3	0.64	2.6	0.8
	1.4	1.12	1.0	25.2	2.3	1.25	2.1	1.1

TABLE A.1.3 OVERTURNING STABILITY FOR GABION-LIKE STRUCTURES

Substituting $L = 0$ into the equations for the width x of active area in the structure-soil interface (after Meyerhof) in section A.6, we obtain:

$$\frac{x}{B} = \frac{\frac{H}{H_w}\frac{g}{g_w} - \frac{1}{3}\left(\frac{H_w}{B}\right)^2 - \frac{2}{3}}{\frac{H}{H_w}\frac{g}{g_w} - \frac{1}{2}}$$

Equally distributed loading on the soil q is calculated as:

$$q = \frac{H_w g_w \left(\frac{H}{H_w}\frac{g}{g_w} - \frac{1}{2}\right)}{\frac{x}{B}}$$

The results are presented in Table A.1.4. Values of *x/B* are consistently between 0.7 and 0.8, indicating small eccentricity of the resultant (about 0.10 to 0.15 of the base width) and, therefore, relatively uniform distribution of the soil loading. The magnitude of this loading is mostly in the range from 10 to 20 kPa. Greater eccentricities and higher loading magnitudes occur with larger units and those which height to width ratio is greater than 1.

Type or commercial name	Wall height H (m)	Water height H_w (m)	Base width B (m)	Weight filled W (kN/m)	$\gamma H / \gamma_w H_w$	$(H_w / B)^2$	x/B	q (kPa)
Hesco Concertainer								
Mil 1B	1.37	1.10	1.1	26.1	2.3	1.07	0.71	28
Mil 2B	0.61	0.49	0.6	6.7	2.3	0.64	0.79	11
Mil 3B	1	0.80	1	18.0	2.3	0.64	0.79	18
Mil 4B	1	0.80	1.5	27.0	2.3	0.28	0.85	17
Mil 5B	0.61	0.49	0.61	6.7	2.3	0.64	0.79	11
Mil 6B	0.61	0.49	0.61	6.7	2.3	0.64	0.79	11
Mil 7B	2.21	1.77	2.13	84.7	2.3	0.69	0.78	41
Mil 8B	1.37	1.10	1.22	30.1	2.3	0.81	0.76	26
Mil 9B	1	0.80	0.76	13.7	2.3	1.11	0.70	20
Mil 10B	2.12	1.70	1.52	58.0	2.3	1.24	0.68	45
Maccaferri Flex Mac								
	0.5	0.40	0.5	4.5	2.3	0.64	0.79	9
	0.5	0.40	1.0	9.0	2.3	0.16	0.88	8
	1.0	0.80	1.0	18.0	2.3	0.64	0.79	18
	1.4	1.12	1.0	25.2	2.3	1.25	0.67	30

TABLE A.1.4 MEYERHOF PRESSURE DISTRIBUTION FOR GABION-LIKE STRUCTURES

A.7.2 JERSEY HIGHWAY BARRIERS

The Jersey highway barrier units are produced in a single shape and size which is shown in Figure A.1.2. The area of the cross-section is calculated in the figure as approximately 0.2 m^2, and the weight of the member is about 4.8 kN/m^1. The weight of water which contributes to the sliding and overturning stability, shown as W_w in Figure A.1.2, is about 1.4 kN/m^1.

The sliding is caused by the horizontal water pressure, i.e. the total force F_w^h = 1.25 kN/m^1. The vertical uplift force F_w^v can be calculated using the formula from section A.7.1, since an impermeable blanket is usually not set up with this system. It should be kept in mind that the value F_w^v = 1.5 kN/m^1, calculated in this way, assumes the seepage through a porous soil underneath (section A.1.1). Keeping in mind that the unit is practically rigid, a small rotation can open a gap of finite width between the member and the soil (which is especially likely in the case of a stiff base - rock mass, road, etc.) and the uplift will then act with its full force i.e. exactly twice as in the case of porous soil without a gap. The factors of safety against sliding and overturning will be significantly reduced in such a case. The calculations are shown in Tables A.1.5 and A.1.6 for both cases described above.

It may be worth noting that case 2 (a gap with full uplift pressure) is possible under the wave action of floodwater; rotational vibrations of the single row of unanchored Jersey units may then occur, followed by excessive sliding and eventual destruction of the barrier.

In the case of a porous soil without a gap, the factors of safety against sliding F_s = 1.0 -1.5 require the friction angle at the base of the unit d = 15^0 - 21^0. With full uplift, this range is increased to d = 22^0 - 30^0. This is about 8^0 higher than for the gabion-like structures, and relatively high in general, limiting the suitability of the system to stiffer soils.

The factors of safety against overturning for the two cases considered are 2.6 and 1.9.

The average hydraulic gradient i = 0.5/0.6 = 0.8 is applicable for the first case only (without a gap).

							F_s = 1		F_s = 1.5	
	Height H (m)	Water height H_w (m)	Base width B (m)	Weight W (kN/m)	Added weight of water Ww (kN/m)	Effective normal force N' (kN/m)	tan δ	δ (°)	tan δ	δ (°)
Case 1: without gap	0.8	0.5	0.6	4.8	1.4	4.7	0.266	14.9	0.399	21.7
Case 2: with gap	0.8	0.5	0.6	4.8	1.4	3.2	0.391	21.3	0.586	30.4

TABLE A.1.5 STABILITY AGAINST SLIDING FOR JERSEY HIGHWAY BARRIERS

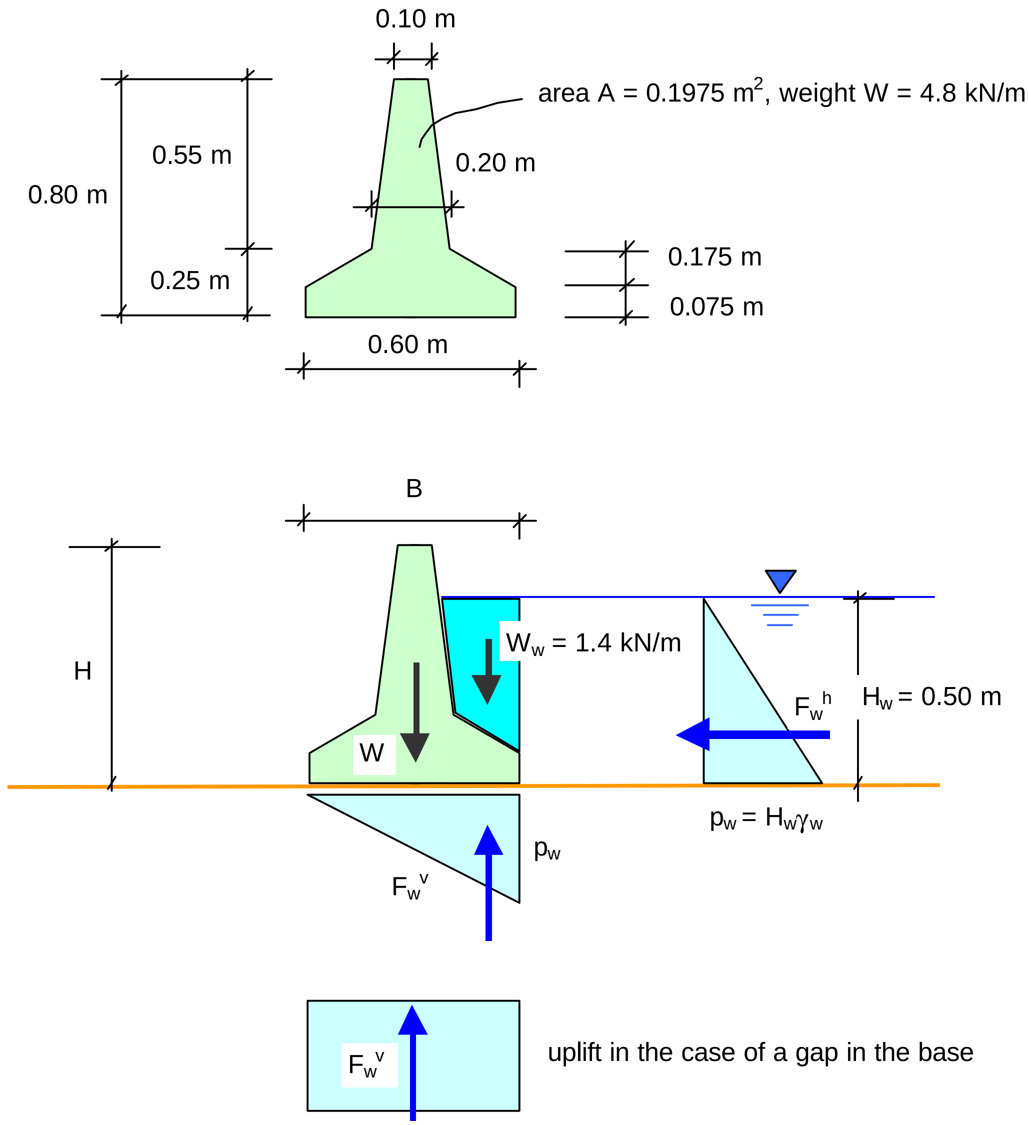

FIGURE A.1.2 STATICAL SCHEME FOR STABILITY ANALYSIS OF JERSEY HIGHWAY BARRIERS

	M_W (kN)	M_w^h (kN)	M_{Ww} (kN)	F_w^v (kN/m)	r_w^v (m)	M_w^v (kN)	F_o
Case 1: without gap	1.44	0.208	0.63	1.5	0.4	0.6	2.6
Case 2: with gap	1.44	0.208	0.63	3.0	0.3	0.9	1.9

TABLE A.1.6 STABILITY AGAINST OVERTURNING FOR JERSEY HIGHWAY BARRIERS

The equations for distributed loading on the base soil after Meyerhof are easily obtained substituting $L = 0$ into the expressions from section A.6:

$$\frac{x}{B} = \frac{2}{B}\frac{Wr_W + W_w r_{W_w} - F_w^h \frac{H_w}{3} - F_w^v \cdot \frac{2}{3}B}{W + W_w - F_w^v}$$

$$q = \frac{1}{B}\frac{W + W_w - F_w^v}{\frac{x}{B}}$$

Table A.1.7 shows the results of the computation. It can be seen that the eccentricity of the resultant force is very small (the consequence of balanced moments by the action of the vertical water pressure W_w) and that the magnitude of the loading is also very low – only 5 to 10 kPa. This is probably due to low levels of retained water and small horizontal pressure.

	M_W (kN)	M_w^h (kN)	M_{Ww} (kN)	F_w^v (kN/m)	r_w^v (m)	M_w^v (kN)	x/B	q (kN/m)
Case 1: without gap	1.44	0.208	0.63	1.5	0.4	0.6	0.89	9
Case 2: with gap	1.44	0.208	0.63	3.0	0.3	0.9	1.00	5

TABLE A.1.7 MEYERHOF PRESSURE DISTRIBUTION FOR JERSEY HIGHWAY BARRIERS

The analysis presented above is based on the method of installation described in Duncan *et al.* (1997). The geomembrane sheeting is used only to wrap the joints to prevent the leaking there. Certain improvement may be achieved if the sheeting is laid in front of the unit, as a kind of impermeable blanket (Figure A.1.3). The vertical uplift pressure is reduced in that way and the overall stability of the barrier increased.

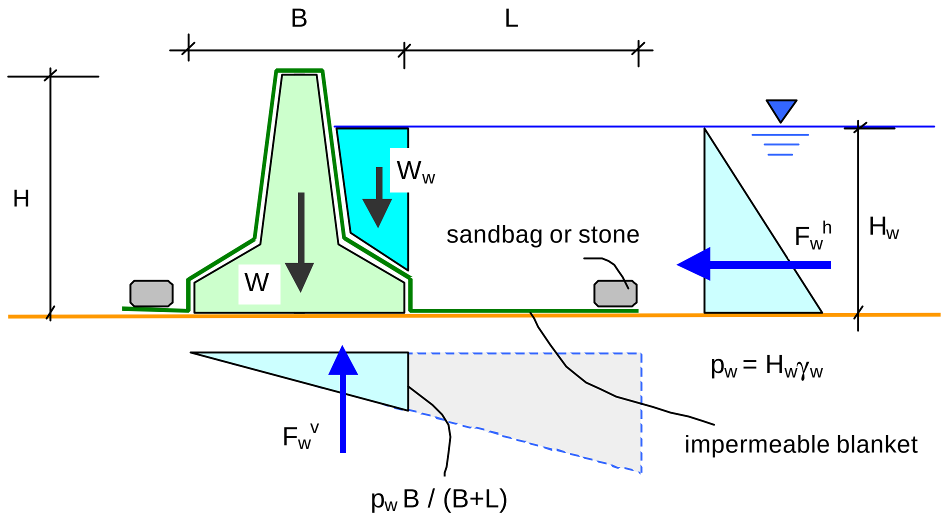

FIGURE A.1.3 JERSEY HIGHWAY BARRIER WITH IMPERMEABLE BLANKET

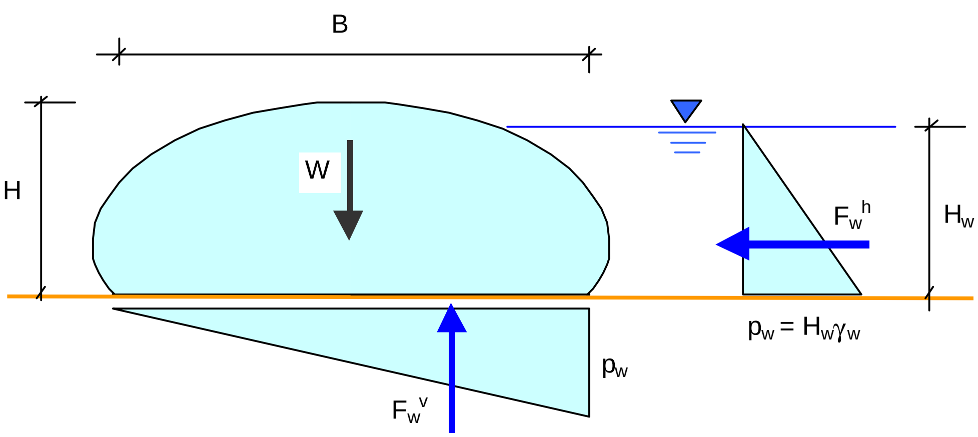

FIGURE A.1.4 STATICAL SCHEME FOR STABILITY ANALYSIS OF WATER-FILLED PLASTIC TUBES

A.7.3 WATER-FILLED PLASTIC TUBES

The formulas presented here are suitable for all tubular structures from section 4.4, with exception of the Clement and the NOAQ systems. The statical scheme for calculation is shown in Figure A.1.4.

These structures are installed without an impermeable blanket so that the equations from section A.7.1 are fully applicable. The computation of the factors of safety against sliding is shown in Table A.1.8.

				Weight filled				F_s = 1		F_s = 1.5	
Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	W (lb/ft)	W (kN/m)	$\gamma_w H_w^2$	$\gamma_w H_w B$	tan δ	δ (°)	tan δ	δ (°)
Water Structures											
	0.31	0.20	0.61	105	1.6	0.4	1.2	0.212	12.0	0.318	17.6
	0.46	0.30	0.81	315	4.7	0.9	2.4	0.131	7.5	0.197	11.1
	0.61	0.46	1.17	470	7.0	2.0	5.2	0.234	13.2	0.351	19.3
	0.92	0.71	1.73	1130	16.8	5.0	12.0	0.230	12.9	0.344	19.0
	1.22	0.91	3.05	2400	35.7	8.2	27.3	0.186	10.5	0.279	15.6
	1.83	1.37	4.73	5800	86.3	18.4	63.5	0.169	9.6	0.253	14.2
	2.44	1.83	5.90	11000	163.7	32.8	105.7	0.148	8.4	0.222	12.5
	3.05	2.74	6.35	13750	204.7	73.7	170.8	0.309	17.2	0.464	24.9
Aqua-Barrier											
				Weight filled				F_s = 1		F_s = 1.5	
Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	W (lb/ft)	W (kN/m)	$\gamma_w H_w^2$	$\gamma_w H_w B$	tan δ	δ (°)	tan δ	δ (°)
Single Baffle	0.61	0.46	1.22	482	7.2	2.0	5.5	0.231	13.0	0.346	19.1
	0.92	0.69	2.14	1415	21.1	4.6	14.3	0.166	9.4	0.249	14.0
	1.22	0.91	3.20	2756	41.0	8.2	28.7	0.154	8.7	0.230	13.0
Double Baffle	0.91	0.69	2.10	1415	21.1	4.6	14.1	0.165	9.3	0.247	13.9
	1.22	0.91	3.20	2756	41.0	8.2	28.7	0.154	8.7	0.230	13.0
	1.52	1.14	4.10	4530	67.4	12.8	45.9	0.144	8.2	0.216	12.2
	1.83	1.37	5.20	6612	98.4	18.4	69.9	0.145	8.3	0.218	12.3
	2.13	1.60	6.20	9364	139.4	25.1	97.2	0.138	7.9	0.207	11.7

TABLE A.1.8 FACTORS OF STABILITY AGAINST SLIDING FOR WATER-FILLED PLASTIC TUBES

The values of d corresponding to F_s = 1.0 (the verge of stability) depend mostly on the tube type, i.e. the shape and the size of cross-section but, in general, the results are very homogeneous, regardless of the manufacturer and the type of product, and they vary between relatively narrow limits, from 8^0 to 13^0. This range may be considered acceptable for most soils, even in the saturated and softened state. The values of d corresponding to F_s = 1.5 vary between 11^0 and 19^0 (with the exception of the heaviest tube of the “Water Structure” - there may be some error in the data). Both ranges are a few degrees lower than those calculated for the gabion-like structures.

Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	Max *i*
Water Structures				
	0.31	0.20	0.61	0.3
	0.46	0.30	0.81	0.4
	0.61	0.46	1.17	0.4
	0.92	0.71	1.73	0.4
	1.22	0.91	3.05	0.3
	1.83	1.37	4.73	0.3
	2.44	1.83	5.90	0.3
	3.05	2.74	6.35	0.4
Aqua-Barrier				
Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	W (lb/ft)
Single Baffle	0.61	0.46	1.22	0.4
	0.92	0.69	2.14	0.3
	1.22	0.91	3.20	0.3
Double Baffle	0.91	0.69	2.10	0.3
	1.22	0.91	3.20	0.3
	1.52	1.14	4.10	0.3
	1.83	1.37	5.20	0.3
	2.13	1.60	6.20	0.3

TABLE A.1.9 AVERAGE HYDRAULIC GRADIENTS FOR WATER-FILLED PLASTIC TUBES

Computation of the hydraulic gradients beneath the tubes is presented in the Table A.1.9. Average hydraulic gradients are, without a doubt, the lowest calculated values in this report.

Computation of the soil loading after Meyerhof does not seem to have much applicability in the case of such a deformable structure. Intuitively, the pressure on the base should be fairly uniform and almost equal (depending on the flexibility of the tube material) to the pressure of the water in the tube. Nevertheless, customary calculation has been done, for completeness of the data and comparison with other methods.

The equations are derived substituting $L = 0$ and $r_W = B/2$ into the expressions from section A.6, to obtain:

$$\frac{x}{B} = \frac{\dfrac{W}{BH_w g_w} - \dfrac{1}{3}\left(\dfrac{H_w}{B}\right)^2 - \dfrac{2}{3}}{\dfrac{W}{BH_w g_w} - \dfrac{1}{2}}$$

$$q = H_w g_w \frac{\dfrac{W}{BH_w g_w} - \dfrac{1}{2}}{\dfrac{x}{B}}$$

Table A.1.10 shows the results of calculation. Values of *x/B* are very homogeneous, ranging from 0.7 to 0.8. The magnitude of the loading q is mostly less than 20 kPa, which is less than with the gabions in section A.7.1. This indicates slightly wider area of application for water-filled tubes.

				Weight filled						
Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	W (lb/ft)	W (kN/m)	$(H_w/B)^2$	$\gamma_w H_w B$	W / $\gamma_w H_w B$	x/B	q (kPa)
Water Structures										
	0.31	0.20	0.61	105	1.6	0.11	1.2	1.29	0.74	2
	0.46	0.30	0.81	315	4.7	0.14	2.4	1.93	0.85	5
	0.61	0.46	1.17	470	7.0	0.15	5.2	1.34	0.74	5
	0.92	0.71	1.73	1130	16.8	0.17	12.0	1.40	0.75	8
	1.22	0.91	3.05	2400	35.7	0.09	27.3	1.31	0.76	10
	1.83	1.37	4.73	5800	86.3	0.08	63.5	1.36	0.77	15
	2.44	1.83	5.90	11000	163.7	0.10	105.7	1.55	0.81	23
	3.05	2.74	6.35	13750	204.7	0.19	170.8	1.20	0.67	28
Aqua-Barrier										
				Weight filled						
Type	Inflated height H (m)	Water height H_w (m)	Base width B (m)	W (lb/ft)	W (kN/m)	$(H_w/B)^2$	$\gamma_w H_w B$	W / $\gamma_w H_w B$	x/B	q (kPa)
Single Baffle	0.61	0.46	1.22	482	7.2	0.14	5.5	1.31	0.74	5
	0.92	0.69	2.14	1415	21.1	0.1	14.3	1.47	0.79	8
	1.22	0.91	3.20	2756	41.0	0.1	28.7	1.43	0.79	11
Double Baffle	0.91	0.69	2.10	1415	21.1	0.1	14.1	1.49	0.80	8
	1.22	0.91	3.20	2756	41.0	0.1	28.7	1.43	0.79	11
	1.52	1.14	4.10	4530	67.4	0.1	45.9	1.47	0.80	14
	1.83	1.37	5.20	6612	98.4	0.1	69.9	1.41	0.79	15
	2.13	1.60	6.20	9364	139.4	0.1	97.2	1.43	0.80	18

TABLE A.1.10 MEYERHOF PRESSURE DISTRIBUTION FOR WATER-FILLED TUBULAR STRUCTURES

A.7.4 CLEMENT SYSTEM

The Clement system may be constructed with widely varying cross-sections, using the standard tube of 17 inches in diameter. A typical triangular shape, made of 6 tubes in 3 levels, is shown in Figure A.1.5. The sliding stability was also calculated for a smaller triangle, made of 3 tubes in 2 levels, but the value of F_s was slightly higher (10 to 15 %) than for the presented six-tube cross-section.

According to the manufacturer's brochure, an ideal circular shape of a tube is slightly deformed when they are stacked one over another, but the overall triangular shape of the cross-section may be considered preserved (a simplification for calculation purposes). The dimensions written in the figure are from the original brochure. The water level H_w is the maximum experimentally observed level for which "there are no deformations of the structure". The base width *B* may be adopted, as shown in the figure, between 34" ≈ 0.85 m (the axial distance between the lateral tubes, for an ideal circular shape of a tube) and 51” ≈ 1.25 m (the total width of 3 tubes). The value of 1.0 m is an average used in calculation.

The values of horizontal and vertical water pressure are:

$$F_w^h = \tfrac{1}{2}g_w H_w^2 = \tfrac{1}{2}\cdot 10\cdot 0.9^2 = 4.1\frac{kN}{m}$$

$$F_w^v = \tfrac{1}{2}g_w H_w B = \tfrac{1}{2}\cdot 10\cdot 0.9\cdot 1.0 = 4.5\frac{kN}{m}$$

The factor of safety against sliding is calculated using the formula:

$$F_s = \frac{\left(W - F_w^v\right)\tan d}{F_v^h}$$

The values of F_s in the range of 1.0 - 1.5 give the following friction angle range:

$$F_s = \begin{cases} 1.0 \\ 1.5 \end{cases} \Rightarrow \quad \tan d = \begin{cases} 0.66 \\ 0.99 \end{cases} \Rightarrow \quad d = \begin{cases} 34^0 \\ 44^0 \end{cases}$$

These values of F_s are too high, meaning that the structure will be unstable in most real situations, although the manufacturer claims successful laboratory testing of the product and even satisfactory operation in actual flood fighting circumstances. Possible cause of this discrepancy may be in reduced uplift pressure beneath the structure. Most probably, the uplift pressure does not act with the full amount calculated above, due to the possibility of drainage between the tubes in the base layer (if the uplift force is taken with 50 % of the above value, the d angle is about 27^0, which may be acceptable). On the other hand, this opens the question of seepage through the soil. The amount of leaking water is then significantly greater than the expected one, i.e. actual average hydraulic gradient is higher than the computed value here:

$$i = \frac{H_w}{B} = \frac{0.9}{1.0} = 0.9$$

Nevertheless, all the problems arisen have to be experimentally tested, as recommended in section 7.2.

The soil loading should be calculated using generic expressions from section A.6. The moments of active forces are:

$$M(W) = W\cdot\tfrac{1}{2}B = 4.65\ kN$$

$$M(W_w) = W_w r_{W_w} = 1.2\ kN$$

$$M\left(F_w^h\right) = F_w^h\cdot\tfrac{1}{3}H_w = 1.23\ kN$$

$$M\left(F_w^v\right) = F_w^v\cdot\tfrac{2}{3}B = 3.02\ kN$$

The effective normal force *N’* is:

$$N' = W + W_w - F_w^v = 6.2\ \frac{kN}{m}$$

and the active width x and loading q are computed directly:

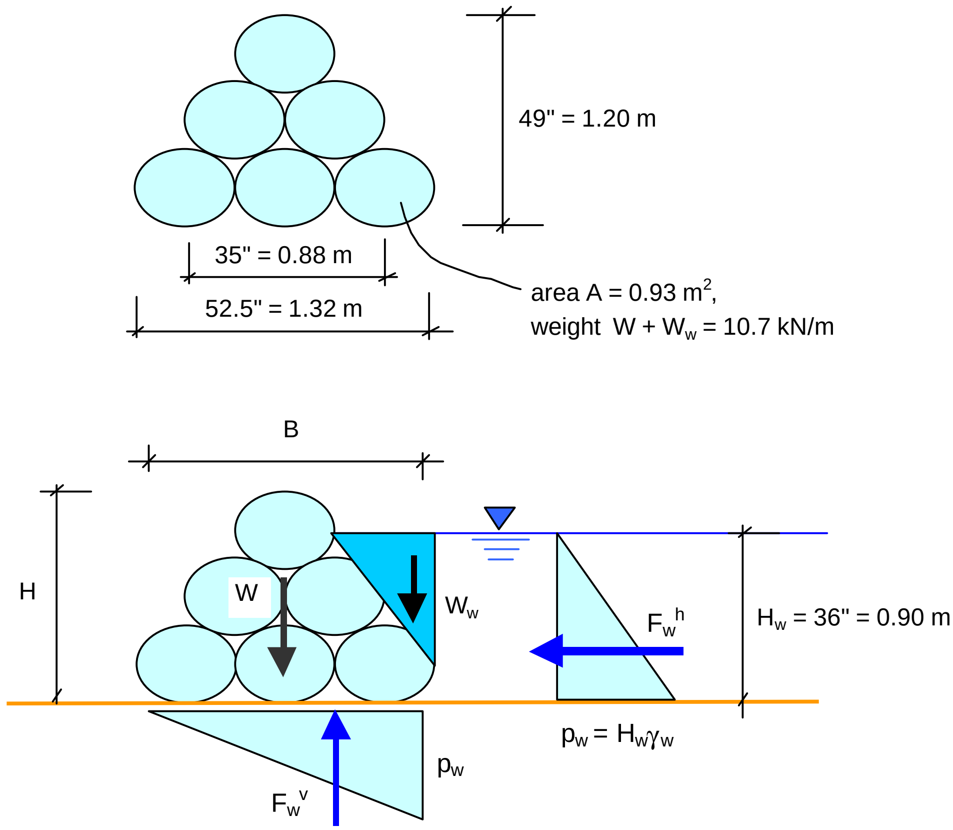

FIGURE A.1.5 STATICAL SCHEME FOR STABILITY ANALYSIS OF THE CLEMENT SYSTEM

$$\frac{x}{B} = \frac{1}{B} \cdot \frac{\sum M}{N'} = 0.26$$

$$q = \frac{N'}{x} = 24\ kPa$$

The eccentricity of the resultant in the base of Clement system is the highest of all considered structures: the force is acting at only *0.10 B* from the downstream toe. Since the structure is flexible, this may suggest large distortions and movements.

Additional information about the Clement system was submitted by the manufacturers late in our review process. The new information referred to the application of an impermeable blanket which wraps the wet side and unfolds in front of the barrier to about 3 metres. Such a blanket was not mentioned in the available commercial material sent by the “Clement Water Diversion Systems” earlier. The application of the blanket has significant positive impacts to the stability analyses presented earlier in this section.

The new structural scheme of the Clement system with a blanket is shown in Figure A.1.6. Since the blanket is not attached to the barrier, it has no static function and its only role is to reduce the seepage through the ground by decreasing the average hydraulic gradient below the structure. With the same input data as used in section A.7.4, the new value of the gradient is now:

$$i = \frac{H_w}{L} = \frac{0.9}{3} = 0.3$$

which is within the range of computed hydraulic gradients for other systems of this type.

In a new analysis of the stability against sliding, the uplift force F_w^v vanishes if one neglects the real pattern of seepage streamlines (assuming zero water pressure at the end of the blanket). Certain influence in reality may also be attributed to the possibility of lateral drainage of seeped water through the space between the tubes in the bottom row. The sliding stability calculation is then simplified to:

$$F_s = \frac{W \tan \delta}{F_v^h}$$

The new values of F_s in the range of 1.0 - 1.5 give the following friction angle range:

$$F_s = \begin{cases} 1.0 \\ 1.5 \end{cases} \Rightarrow \tan \delta = \begin{cases} 0.38 \\ 0.57 \end{cases} \Rightarrow \delta = \begin{cases} 21^0 \\ 30^0 \end{cases}$$

These new friction angles δ are greatly reduced when compared with those from section A.7.4 (calculated for the barrier without a blanket) but they are still the highest in the group of water-filled tubular systems. Nevertheless, the use of a blanket significantly widens the range of soils to which the Clement system may be applied.

On the other hand, the introduction of a blanket prolongs the time needed for installation and makes it more difficult than it was explained in the manufacturer's brochure. There are probably certain increases in the purchase price and the overall cost of the system as well.

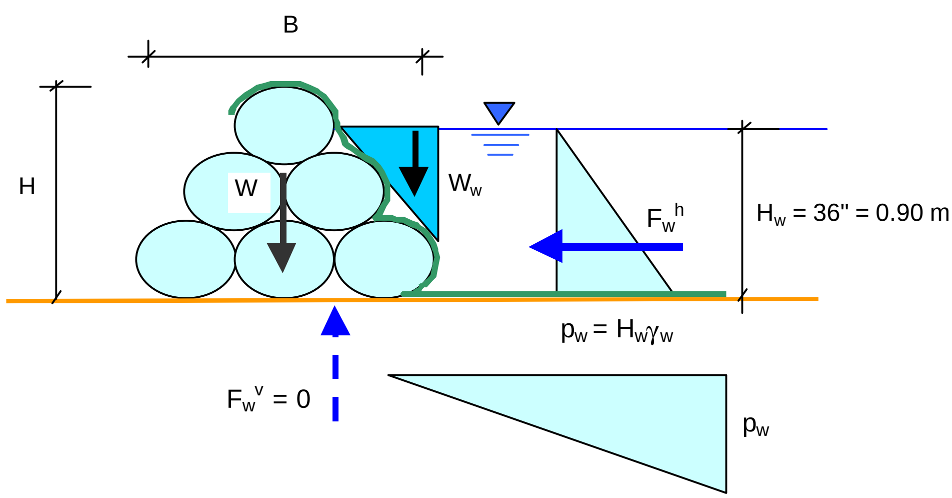

FIGURE A.1.6 NEW STATICAL SCHEME FOR THE CLEMENT SYSTEM WITH AN IMPERMEABLE BLANKET

A.7.5 NOAQ SYSTEM

The statical scheme of the NOAQ system is shown in Figure A.1.7. All geometrical data in this figure were read from the sketches provided in the product brochure. They should be taken as preliminary, according to the manufacturer, although it does not change basic findings and conclusions from the stability calculation shown here. The strongest point of the system is in extremely clear idea of water pressure as an active force to provide the friction necessary for the sliding stability. The length of the blanket is a regulating means for the magnitude of the normal force. This allows very simple design changes, if they are necessary.

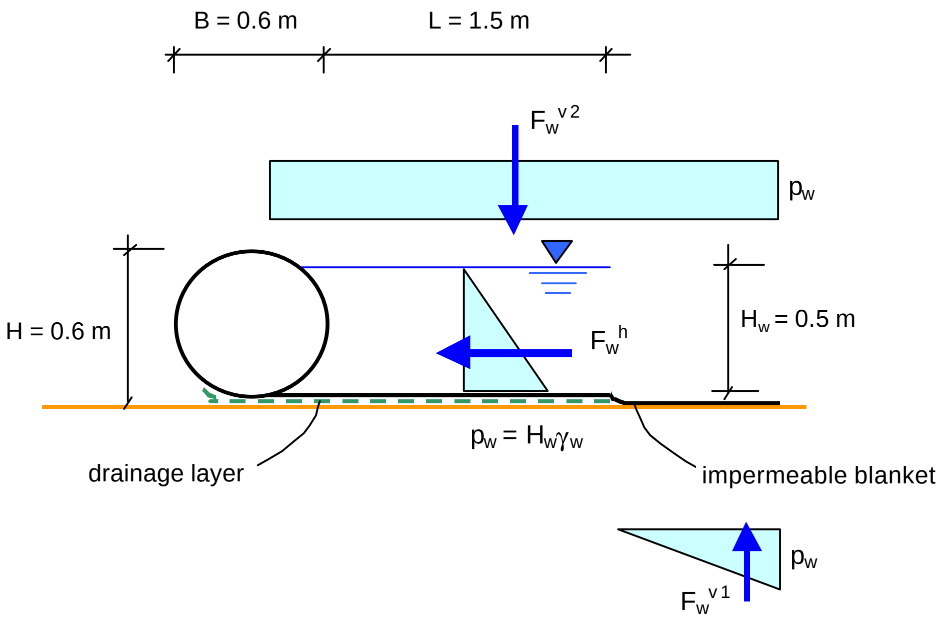

FIGURE A.1.7 STATICAL SCHEME FOR STABILITY ANALYSIS OF THE NOAQ SYSTEM

The active length of the blanket (the “skirt” in the brochure) is the part underlined by a drainage layer. It is actually little less because of the seepage streamline pattern (the water head is not zero at the end of the drainage layer), but this may be neglected since the blanket can be simply extended to a needed length. The effective normal force on the skirt *N’* is a difference between the upward and the downward acting water pressures F_w^{v1} and F_w^{v2}. To simplify the computation, only the pressure on the active blanket length is taken into account. This assumption is on the side of safety, and probably compensates the error made by the definition of the active blanket length (equal to the drainage layer length).

With the dimensions from Figure A.1.7, the forces needed are calculated as:

$$F_w^h = \tfrac{1}{2} g_w H_w^2 = \tfrac{1}{2} \cdot 10 \cdot 0.5 = 1.25 \frac{kN}{m}$$

$$N' = g_w H_w L = 10 \cdot 0.5 \cdot 1.5 = 7.5 \frac{kN}{m}$$

The factor of safety against sliding can be computed from a simple formula:

$$F_s = \frac{N' \tan d}{F_w^h} = \frac{g_w H_w L}{\frac{1}{2} g_w H_w^2} \tan d = \frac{2L}{H_w} \tan d$$

i.e. the friction angle d is obtained from the expression:

$$\tan d = \frac{H_w F_s}{2L}$$

As usual in this report, the necessary friction angles d are determined for the range of factors of safety Fs:

$$F_s = \begin{cases} 1.0 \\ 1.5 \\ 2.0 \end{cases} \Rightarrow \quad \tan d = \begin{cases} 0.17 \\ 0.25 \\ 0.33 \end{cases} \Rightarrow \quad d = \begin{cases} 10^0 \\ 14^0 \\ 18^0 \end{cases}$$

The necessary friction angles d for the NOAQ system are the lowest values for all the systems investigated in this report, which means that the structure has no practical restrictions regarding the underlying soil. The above calculated d values may even be further reduced by simple extension of the blanket. Of course, it is necessary to experimentally test the basic principle on which this system is based - the functioning of the drainage layer (see section 7.2).

The average hydraulic gradient for seepage through the soil beneath the system is calculated as:

$$i = \frac{H_w}{L} = \frac{0.5}{1.5} = 0.3$$

again under assumption of full active length of the drainage layer. This value of average hydraulic gradient is also the lowest value for all the systems investigated in this report.

Calculation of Meyerhof pressure does not make sense in the case of NOAQ system: neglecting the stiffness of the blanket, it can be said that the water pressure directly acts onto the ground.

APPENDIX 2: MANUFACTURERS' DATA (VALID AT DECEMBER 31, 1998)

Aqua-Barrier, Inc.
9597 Jones Rd., Suite 335
Houston, TX 77065
Tel: (800) 245-0199
Fax: (281) 807-1218
E-mail: barrier1@ix.netcom.com
Internet: www.aquabarrier.com

Aqua Dam and Diversion Ltd. ("Aqua Dam"™)
6970 - 10th Avenue SE
Salmon Arm, British Columbia, V1E 4M3
Tel / Fax: (250) 832-1332

Clement Water Diversion Systems Ltd.
Suite 308, 602 - 11 Avenue SW
Calgary, Alberta, T2R 1J8
Tel: (403) 234-0800
Fax: (403) 234-0773
E-mail: info@clemwater.com
Internet: www.clemwater.com

Doublewal Corporation
7 West Main Street
Plainville, CT 06062
Tel: (860) 793-0295

FCA, Flood Control America (Distributors of GOH DPS 2000®)
560 Herndon Parkway, Suite 310
Herndon, VA 20170
Tel: (703) 707-0300
Fax: (703) 707-0500
Internet: www.floodcontrol.com

GeoCHEM, Inc. (Distributor of "Water Structure"™)
106 Lake Avenue South
Renton, WA 98055
Tel: (425) 227-9312
Fax: (425) 227-8797
Internet: www.geocheminc.com

Geodesign AB (Aqua Barrier Flood Fighting System)
Teknikrigen 1
583 30 Linkoping, Sweden
Tel: +46 13 211 955
Fax: +46 13 211 958
E-mail: kullberg@geodesign.se
Internet: home6.swipnet.se/~w-67096

Geomodular Structures (ModuWall™)
15 Brookridge Drive
Avon, CT 06001
Tel: (203) 673-5154

GOH - Gesellschaft fur operativen Hochwasserschutz mbH (GOH DPS 2000®)
Dieselstrase 9
50996 Koln, Germany
Tel: +49 (0) 2236 / 96 25 83
Fax: +49 (0) 2236 / 96 25 88
E-mail: goh@Handwerkonline.de
Internet: www.handwerkonline.de

Hesco Bastion Limited (Concertainer®)
Unit 37, Knowsthorpe Gate
Cross Green Industrial Estate
Leeds LS9 ONP, West Yorkshire, England
Tel: +44 113 248 6633
Fax: +44 113 248 3501

Maccaferri Gabions of Canada Ltd. (Distributor of Flex Mac®)
10548 - 82 Avenue
Edmonton, Alberta, T6E 2A4
Tel: (403) 433-1704
Fax: (403) 439-8110

Mid-Atlantic Permacrib
PO Box 238
Annapolis Junction, MD 20701
Tel: (301) 490-0055

The Neel Company (T-Wall)
6520 Deepford Street
Springfield, VA 22150
Tel: (703) 922-6778

NOAQ Nordisk Aquateknik AB (NOAQ Flood Fighting System)
PO Box 343
SE - 824 27 Hudiksvall, Sweden
Tel: +46 650 152 50
Fax: +46 650 75601
E-mail: sigurd.melin@terrafirma.se
Internet: www.noaq.se

Portadam, Inc.
5888 West 71st Street
Indianapolis, IN 46278
Tel: (317) 388-1866
(800) 488-0030
Fax: (317) 388-1977
Internet: www.portadam.com

Richardson, Cecil A.
105 Gardenia Ct.
Upland, CA 91786
Tel: (909) 982-8479

Sanilogical Projects
2001 River Drive
New Westminster, British Columbia, V3M 4V8
Tel: (604) 524-3458
Fax: (604) 524-4058

Sumitomo Electric Industries
551 Madison Ave
New York, NY 10022
Tel: (212) 308-6444
(508) 755-0440

SWI Mitigation Services
3289 Prospector Drive
Casper, WY 82604
Tel: (307) 266-4771

The Trading Force Limited (Distributor of Hesco Concertainer®)
1350 Falling Brook Ridge
Orleans, Ontario, K4A 2A8
Tel: (613) 834-7697
Fax: (613) 834-6756

Water Wall
Scott Russell
P0 Box 1734 Stn. Main
Brantford, Ontario, N3T 5V7
Tel: (888) 875-2169
Internet: www.waterwall.com

Water Structures Unlimited
PO Box 206
Carlotta, CA 95528
Tel: (800) 693-5055
Fax: (707) 786-2116
E-mail: wsu@humboldt1.com