9 Floodwalls and flood embankments

9.1 Introduction

The construction of floodwalls and embankments has been the traditional means of protecting low-lying communities and infrastructure against flooding. This chapter covers the design of new and remedial works for any form of floodwall or embankment that can be referred generically as ‘flood defences’. This includes temporary flood defences and the recently introduced demountable flood defences. The photographs and diagrams within the chapter illustrate a range of design solutions. These are presented as examples and are not a substitute for proper investigation and design to suit each specific site.

There are many thousands of kilometres of flood embankments and hundreds of kilometres of floodwalls alongside our rivers and streams. The majority of the major defences in England and Wales are maintained by the Environment Agency, but there are also many walls and embankments along ordinary watercourses that are owned by third parties who undertake their maintenance responsibilities with varying degrees of commitment.

Although both Defra’s and the Environment Agency’s current strategies for flood risk management place significant emphasis on alternative means of reducing or mitigating the risks of flooding, floodwalls and embankments will continue to provide one of the most important means of protecting houses, businesses and infrastructure against flooding for the foreseeable future. In many locations, floodwalls or embankments are the only practicable means of reducing flood risk. As Figure 9.1 shows, floodwalls can even be incorporated into landscape design.

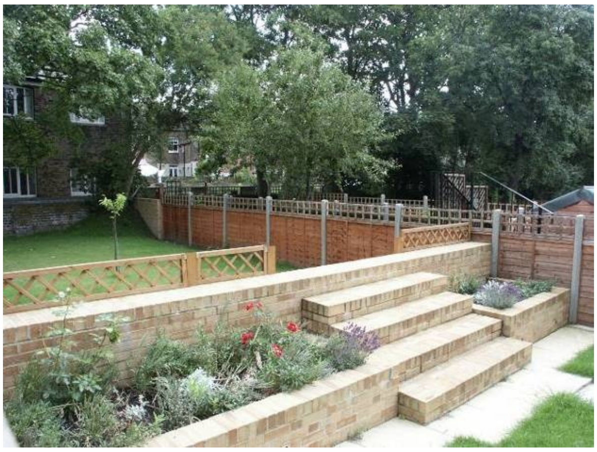


Figure 9.1 Landscaped floodwalls

The incorporation of flood defences into private gardens calls for imaginative design. Where the gardens form part of an active floodplain, the defence should ideally be set back from the river’s edge so that loss of floodplain is minimised. Thus the residents retain some garden which is defended and some which is not. Flood gates can be provided if steps over the defence are not acceptable. In the example shown, safety could be improved by adding a handrail to the steps. For disabled access, a gate would be better (a ramp would probably be too long in this instance).

Nevertheless there are situations where floodwalls and embankments cannot be considered to be a sustainable option. In such cases, the only viable options may be to:

- improve flood warning;
- provide individual flood protection measures to affected houses;
- make the affected houses more flood resilient.

In the longer term, some highly vulnerable property and infrastructure may have to be abandoned, demolished or relocated. Unpalatable though it may seem to abandon developed areas, it is sometimes the only realistic solution to remove the risk. It also has the advantage of returning much-needed floodplain to the river.

All flood defence structures are assets that have to be managed and maintained to ensure that they perform their intended function and remain serviceable throughout their lives. It is therefore important that the whole lifecycle of a flood defence is considered from the outset, including consideration of its eventual decommissioning.

In line with current government thinking, as set out in *Making space for water* (Defra, 2005), designers should also seriously consider the alternatives to flood defences in the early stages of planning.

9.2 Fundamentals

This chapter defines a flood defence as any structure that is designed to (or by virtue of its nature and location is able to) contain floodwaters and to reduce the probability of flooding in the defended area. In the UK, such defences rarely exceed 5m in height and more commonly are 1–3m high.

The traditional approach to the design of such flood defences was to estimate a design flood level and then calculate the required elevation of the top of the flood defence by adding on a suitable freeboard. This guide adopts a risk-based approach to the design and assessment of flood defences and therefore considers the performance of the whole flood defence system under a wide range of conditions, including extreme floods. The fundamental principles that underlay this approach are presented in Sections1.2 and 1.3.

Although the primary function of a wall or embankment may be flood defence, such structures also frequently have a secondary function – quite often with the aim of enhancing the environment or improving the amenity or both. Indeed, for any works commissioned or consented by the Environment Agency, there is a duty under the Environment Act 1995 to conserve and enhance the natural beauty of rivers and coasts. There are some notable examples of this multi-function approach, such as at Gainsborough and Perth (see Figure 9.2), where the construction of urban flood defences has been used as an opportunity to improve an urban waterfront. Further guidance on landscape improvement as part of fluvial design is given in Chapter 5.

Figure 9.2 Perth flood alleviation scheme

In this scheme, the designers took the opportunity to enhance the riverside through the creation of attractive river walls with a high quality masonry finish. The flood defences have been sympathetically incorporated into a major improvement of the river frontage. This is a really good example of a 'win–win' project.

A floodwall can be constructed from brick, masonry, concrete, sheetpiling or a combination of these materials. Steel is the most common material for sheetpiles, though the alternative of plastic should not be overlooked for situations where the lower inherent strength is acceptable. A flood embankment is constructed from earth, and may include a clay core to reduce seepage through the embankment. Both floodwalls and flood embankments may require a cutoff to limit seepage through the foundations (see Section 9.9).

The traditional temporary barrier against flooding is the sandbag wall, which offers flexible and versatile emergency protection, but cannot produce a watertight defence and requires a lot of effort to erect and remove. Temporary and demountable defences (see Section 9.10) can be constructed from timber, steel, aluminium, plastic and various combinations of these materials (Ogunyoye and van Heereveld, 2002).

Very few defences are completely watertight; most exhibit some leakage or under-seepage through the foundation material when holding back a flood. The design should cater for this.

It is fundamental that a flood defence structure remains stable under hydraulic loading, even if the loading is prolonged or if the defence is overtopped. Although some damage to a flood defence may be expected in an extreme flood, this should not impair the serviceability of the structure and under no circumstances should the defence collapse during a flood. The assessment of existing defences and the design of new structures must therefore consider all potential failure modes (see Section 9.6). The greater the height of a flood defence, the more serious would be the consequences of a collapse of the wall (because the flood wave generated would be more damaging). High walls and embankments thus merit particular attention, both in their design and in asset inspection.

9.3 Wall or embankment?

Table 9.1 summarises the main factors that determine the choice between a floodwall and an embankment.

Table 9.1 Factors determining the choice between a wall and an embankment

Factor	Wall	Embankment
Space	Ideal for situations where space for the defence is limited.	Takes up a lot of space. A 2.5m high embankment typically requires a footprint at least 15m wide.
Environment	Ideal for urban situations where the defence can be designed to blend into the local infrastructure.	Ideal for a rural setting, but can be used in an urban environment if space permits (for example, in a riverside park).
Cost	Depends on the materials used (especially cladding), access for construction and foundation conditions.	Cost mainly depends on the source of fill material. Use of locally obtained material can significantly reduce costs and the overall environmental impact.
Foundations	Walls and embankments can both be complicated by the presence of weak or permeable foundations.	
Asset management	Generally require minimal maintenance, but the design should address the need for inspection of critical elements to ensure continued functionality.	Require regular inspection and maintenance, including grass cutting, control of unwanted vegetation, repair of damage by cattle and dealing with infestation by burrowing animals.
Under-seepage	Walls are likely to require a cutoff against seepage when constructed on permeable soils.	Embankments may require a cutoff against seepage on permeable soils, but the longer seepage path often makes this less of an issue than with a wall.

Figures 9.3 and 9.4 illustrate the features of a typical floodwall and a typical embankment respectively. These are intended to be illustrative only. More detailed examples of floodwalls are given in the series of case studies that are referenced through this chapter. Floodwalls are described in Section 9.7 and embankments in Section 9.8.

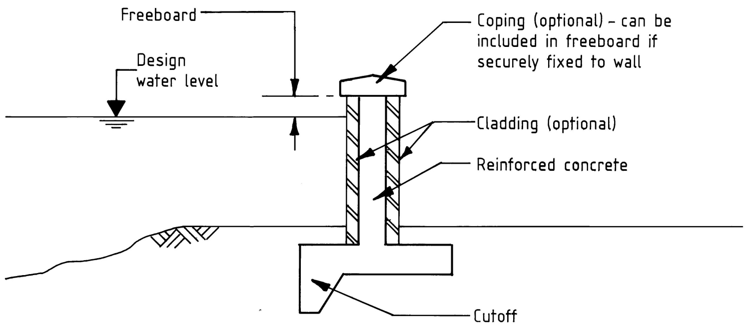


Figure 9.3 Typical floodwall

The diagram illustrates the main components of a floodwall. A cutoff is often required to reduce seepage under the wall (in which case it would generally be deeper than illustrated). The cutoff also helps to stabilise the wall (against sliding – see Section 9.6).

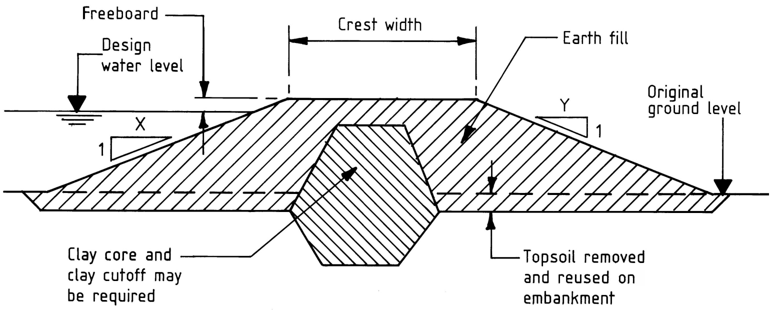


Figure 9.4 Typical flood embankment

A flood embankment has a much larger footprint than a floodwall and therefore requires considerably more space. A clay core may be required to reduce seepage through the embankment. This can be trenched into the foundation to reduce seepage underneath the embankment.

9.4 Design crest level

The crest level of a flood defence is a fundamentally important parameter for the design, construction and long-term maintenance of the defence. This is because it establishes the standard of defence, or the severity of the flood against which the flood defence provides protection. This has historically been expressed in terms of the return period of the flood for which the defence was designed (see Section 2.4.1). The design crest level is then determined by adding a suitable freeboard to the appropriate design flood level.

The concept of freeboard and methods of assessing freeboard are described in Environment Agency R&D Technical Report W187 (Kirby and Ash, 2000). Freeboard is, in effect, a safety margin that allows for uncertainties. These include the uncertainties associated with the estimation of the design water level as well as wave effects, construction tolerances and long-term deterioration of the defence.

Allowances for waves are generally not large for a typical fluvial defence, but need to be increased where the expanse of water is large, such as a wide floodplain, or where there are other factors such as boat-generated waves.

Allowances for deterioration of the flood defence standard include:

- settlement of the defence due to consolidation of the foundation and, in the case of an embankment, consolidation of the earth fill;
- degradation of the crest, such as wear to an embankment crest caused by cattle and agricultural machinery;
- the loss of wall coping stones due to vandalism and vehicle damage.

The uncertainties that impact directly on design water level include:

- confidence limits for the hydrological and hydraulic data and calculations;

- inaccuracies inherent in any physical or analytical models used;
- variations in assumptions made about channel shape and form, hydraulic roughness, maintenance regime and sedimentation.

The impact of future climate change on the flood defence level is normally allowed for in the choice of design flood (for example, by adding 20% to the present day design flood flow). Defra provides guidance as to how to incorporate climate change impacts into a flood alleviation scheme (see Section 2.8.1).

Although the concept of a design water level and a freeboard remains useful, it is also appropriate to examine the performance of any flood defence in the context of the whole system. This approach is most easily understood by considering the analogy of the weakest link in the chain. But it is more complex than this and involves not only a consideration of how the system responds to rising flood levels, but also how this impacts on the defended area, in particular in terms of routes for floodwater and the speed of inundation when part of the system has been overtopped (see Chapter 1).

Designers must also consider whether it is appropriate to construct a defence to its full height from the beginning, or to design for construction in two or more stages. This latter approach may be preferable where there is significant uncertainty about the allowances for future increases in flood levels (for example, due to climate change). In this case the wall (or embankment) can be designed such that future heightening can be carried out at a later date if necessary (‘adaptable design’), thus delaying (and possibly even avoiding) some of the investment cost. In practical terms this would mean proving a foundation for the full height wall or embankment, but only initially constructing the wall or embankment to an intermediate height which is sufficient for the foreseeable future (perhaps 10 to 20 years).

9.5 Performance in floods

The assessment of the performance of a flood defence structure in flood conditions is addressed from three different perspectives depending on the situation.

- **For new flood defence structures**, the designer starts with a ‘clean sheet’ and is able to develop the design based on the site conditions (including foundations, access, and the materials available). The design must be tested for the full range of flood conditions to ensure it remains serviceable under all loading conditions.
- **For existing defences that require improvement**, the design emphasis – at least in the initial phase – shifts towards the assessment of the performance of the existing structure, in particular in terms of potential failure modes (see Section 9.6). To give the designer confidence in the functionality and safety of a rehabilitated or adapted structure, this is likely to require considerable investigation into the original design and the current condition of the elements that make up the defence. This process is particularly complicated when floodwalls are constructed on an urban river frontage, where the stability of the wall depends on a substantial old quay or wharf structure that is likely to have been strengthened or rehabilitated in the past, but whose condition may be difficult to determine. In the final analysis, it may be that rehabilitation proves uneconomic or impractical and complete replacement becomes necessary.
- **For operational defences**, the assessment is focused on the current condition and ability to perform safely in flood conditions. Initially, condition assessments are based on visual inspection. If potential problems are observed, experienced engineers are called upon to assess the significance of, for example, a crack in a concrete floodwall or a surface slip in the face of an embankment.

The full range of flood conditions should include:

- flood level at design level;

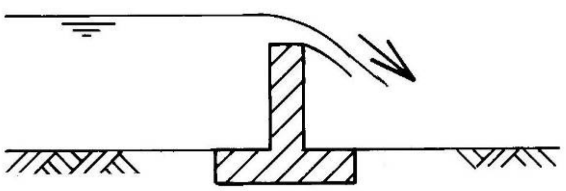
- flood level at crest level;
- flood level above crest level resulting in overtopping;
- rapid drawdown (see Section 9.6) of water level following a flood;
- the possibility of floodwaters being retained on the defended side after a flood has receded (reversing the normal hydraulic loading).

No flood defence gives absolute protection: there is always a residual risk. The highest probability of failure of a floodwall or embankment tends to be associated with overtopping. The design process, whether for a new or an existing defence, must therefore examine all foreseeable failure modes. These are often driven by extreme flood levels that result in overtopping, but also by sustained high water levels or rapid drawdown of water level, which can destabilise a foundation or cause slips in embankments. The ability of a defence to withstand extreme loading conditions is termed 'resilience'. This does not necessarily mean that the defence provides full protection for floods greater than those for which it was designed, but it does mean that the defence should not fail catastrophically in such circumstances.

9.6 Failure modes

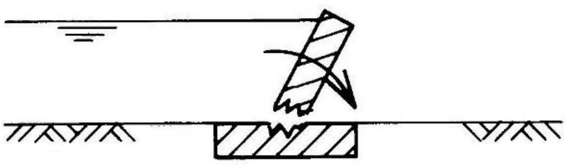
The most common failure modes for flood defences are listed in Box 9.1, using a floodwall to illustrate each case. The notes explain the modes and indicate when they also apply to flood embankments.

Box 9.1 Common failure modes for flood defences



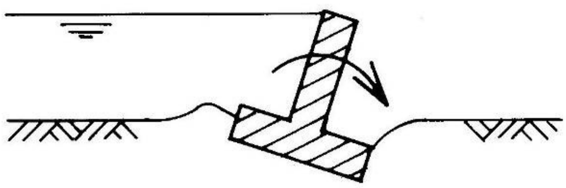
Overtopping leading to failure

Overtopping of a defence does not necessarily result in failure – the defence may have been designed to be resilient if overtopped. However, if the defence collapses during overtopping, the consequences may be more severe than if there were no defence. Overtopping of an embankment can wash away the crest, leading to a breach.



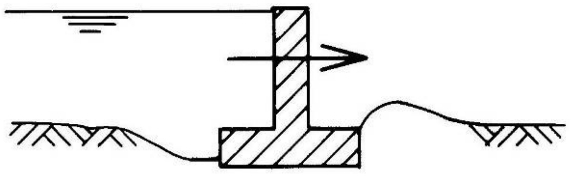
Structural failure

In this case there is a structural failure of part of the defence, leading to loss of ability to retain water. A sudden collapse can be very dangerous, as it can lead to rapid inundation in the defended area without warning. A breach is the equivalent mode for an embankment. Collapse can also result from erosion of the riverbank if the defence is close to the river.



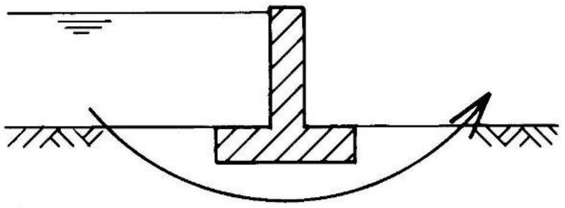
Rotation

Here the defence has rotated under the action of the hydrostatic load, which may include uplift under the base of the wall. A partially rotated wall may remain stable for some time, but the defence level is likely to have been compromised and there remains a risk of collapse under future loading.



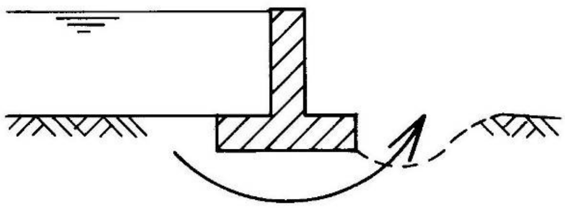
Sliding

This may appear to be a ‘safe’ form of failure when viewed in cross section. In reality, the sliding may open up cracks between adjacent parts of the defence and the foundations may be compromised.



Seepage

If the quantity is modest, seepage under the defence can usually be dealt with by pumping. Excessive seepage can lead to local flooding and may damage the foundations (see piping below). Seepage can occur through an embankment as well as under it, often as a result of damage by burrowing animals. Local collapse of the embankment may result.



Piping

In extreme cases, seepage flow under a defence can cause the soil on the defended side to become buoyant, creating a void. This can lead to sliding or rotational failure of the wall, or a breach in an embankment. Flow through an embankment can also result in piping failure. The addition of a cutoff to lengthen the seepage path is often the most effective way to avoid piping failure.

No flood defence should collapse suddenly in extreme floods, so it is necessary to consider how a defence performs when overtopped. One way of reducing the damage to the defence during overtopping is to ensure that there is no localised overtopping (that is, by having a uniform crest level without low spots).

Although floodwalls may seem less vulnerable than embankments, water cascading over a wall can destabilise the foundation, leading to sudden collapse. The solution to this problem (assuming that heightening the floodwall is not an option) is to protect the foundation on the landward side of the wall by some form of hard surfacing (this could double as an access way), or by creating a half-bank over which overtopping flow could be safely conveyed for the period for which it is likely to occur. Such solutions are likely to be particularly appropriate where the length of wall being overtopped is deliberately limited in extent, as may be the case where a short length of wall has been designated as the preferred route for overtopping flows in extreme floods.

Flood embankments are normally more likely to fail if overtopping is concentrated over a short length. Long lengths of flood embankments (such as those that separate a river from a flood storage area) can usually overtop safely, provided the flow is spread evenly over a long length of embankment. Where an embankment is designed to overtop over a limited length (a spillway), this section of the embankment should be reinforced. The reinforcement can range from a geotextile incorporated into the topsoil to gabion mattress or concrete block revetment systems.

Flood embankments can fail when the flood recedes if the external water level drops more quickly than the rate at which porewater pressures can be dissipated in the soil body – a situation often referred to as ‘rapid drawdown’. This is less dangerous than failure on a rising flood, but should be considered as a design case if such conditions are possible.

It should also be appreciated that, if it is overtopped during a flood, a defence may retain floodwater on the defended side after the flood has receded. This may mean that a sluice or similar structure must be provided to allow evacuation of the floodwaters. It also requires a defence that can resist water pressure in two directions (from the river side and from the defended side).

Any type of flood defence can trap surface water runoff from the hinterland (that is, from the defended area itself and from the surrounding higher ground). Flooding from surface water runoff is an increasing problem, so it is vital to consider how the drainage system may be interrupted by any flood defence. The common solution is to provide flap-gated outfalls through the defence, though these run the risk of compromising the defence if they become wedged open (accidentally or deliberately) during a flood. Another option is to pump the surface runoff, in which case the sizing of the pumps and their reliability of operation become crucial issues. Reliance on a single pump is generally avoided by the provision of a standby, but even this cannot guarantee reliability if a power failure is possible.

Food defences located close to the edge of a river may be vulnerable to damage by erosion of the riverbank. It may be necessary to protect the riverbank against erosion (see Chapter 8). Where space permits, it is preferable to set the defence back from the river, retaining more of the active floodplain and creating a more attractive riverside environment.

Further information about the performance of floodbanks is given in *Management of flood embankments – a good practice review* (Defra and Environment Agency, 2007).

9.7 Floodwalls

9.7.1 Types of floodwall

There are two basic types of floodwall:

- those that also form part of the river frontage, such as a wharf, retaining wall, or quay;
- those that are remote from the river, generally with the sole purpose of providing a flood defence.

Defences that form part of the river frontage usually have deep foundations and considerable overall height. Often such walls have been in existence for many years and their flood defence function has increased with time, with progressive heightening of the crest level. Such defences need careful investigation if they are to be upgraded or refurbished to provide an acceptable service life.

The form of construction of such walls includes brick, masonry, timber, sheetpiling and concrete.

The main factors to consider include:

- the type, condition and stability of any existing foundations;
- the presence of historic wall elements that might make driving of new sheetpiles very difficult (old timber piles that have rotted away often leave embedded parts in surprisingly good condition – these can present significant obstructions to the driving of new piles);
- there may be a requirement to conserve historic elements of a wall;
- the need for tie rods or ground anchors to restrain the wall against overturning (commonly used with steel sheetpile walls – see Section 9.13);
- the need for access ways in the defence to allow the continuation of business and leisure activities on the river frontage;
- traffic loading surcharge on the landward side (these can be particularly onerous at an operating wharf or quayside);
- additional loadings on the wall from mooring or boat impact;
- the need to accommodate diurnal variation in river level for tidal rivers (which may result in daily changes in the hydrostatic pressure direction on the wall).

Should the existing river frontage not be suitable for upgrading or rehabilitation (having reached the end of its service life), the option of setting the floodwall back from the frontage should be considered. This has implications for the flood defence of the land between the river and the floodwall, but may be the only acceptable option if the flood defence is to remain independent of the frontage and thereby not dependent on its stability. Such a situation is likely to arise when the party responsible for constructing and maintaining the flood defence does not have (and does not want to take on) any responsibility for the existing river frontage structures.

For defences remote from the river, construction tends to be more straightforward. Concrete (both precast and insitu) is the most common form of construction, often with some form of cladding or decorative finish. Brick and masonry can be used, but these either have to be massive structures (unless very low in height) or be reinforced with steel bars. Low brick walls can be formed by constructing a tied cavity wall on a concrete foundation, with reinforcing bars extending from the foundation up the cavity. The cavity can then be filled with concrete, during which the brick skins may need external support while the concrete in the cavity hardens.

Where a cutoff is required (see Section 9.9), a sheetpiling wall offers the advantage of providing both the cutoff and the wall – though it is normal to clad the wall with brick or masonry to improve its appearance (see Case study 9.1). Where space permits, one side of a sheetpile wall can be given a 'half-bank', so that it appears to be a flood embankment from that side. Figure 9.5 shows an example where the floodwall has been combined with an embankment.

Figure 9.5 Flood embankment combined with floodwall

Here a floodwall has been combined with an embankment to reduce the footprint close to a residential property. In this case, the embankment does not add to the stability of the wall because the hydrostatic pressure comes from the embankment side. If the wall were to be located on the river side, then the embankment can provide support to the wall when it is subjected to high flood levels.

Standard precast wall concrete units offer the advantage of speed of construction, but may lead to wastage if the ground level along the wall alignment is very variable, requiring the wall height to vary. (The advantage of using precast units is reduced if many different sizes are needed or if the largest size required is used throughout.) Cast insitu walling is more often used where there are frequent changes of direction or wall height.

Where a floodwall passes through private land, there may be a need for an easement to ensure the right of access for inspection and maintenance is provided for ever.

9.7.2 Materials for floodwalls

Some of the issues surrounding the choice of materials for floodwalls have been touched on above. The fundamental considerations are:

- **Visual acceptability** – this can be resolved by cladding a structural wall with a decorative finish, the choice of cladding depending on local circumstances and planning permission;
- **Durability** – especially for those elements in frequent contact with water (particularly for steel);

- **Resistance to vandalism** – coping stones on brick or masonry walls can be a target, but most other forms of construction are not prone to vandalism that affects their correct functioning (though graffiti are often a problem);
- **Use of recycled materials** should be considered, where practicable (for example, second-hand steel sheetpiles could be used for a cutoff where strength, durability and visual appearance are less significant issues than for exposed structural sheetpiling).

Figure 9.6 High floodwall with large floodgate for access – Frankwell, Shrewsbury

Massive flood defences like this can only be justified in certain circumstances. They create a physical and visual barrier, although these may not always be undesirable attributes.

Walls of this height are substantial structures, which have to be safe against very high hydrostatic loading conditions. They are therefore expensive to construct.

The gate adds another complication and a maintenance liability. In this instance the floodgate provides access for machinery to maintain a bowling green.

Durability is particularly an issue for those elements of the structure that would be difficult to access for inspection or repair during the life of the structure. Tie bars and anchor rods are two such elements that require a belt-and-braces approach to corrosion protection because they cannot readily be inspected (being below ground) and are expensive to replace. Such elements should be designed to achieve or exceed the service life of the structure without any maintenance.

It is important that the cladding is fixed firmly to the wall structure such that the risk of it becoming detached (as a result of vandalism or accidental damage) is small. For the side of the wall that will be in contact with water during floods, the use of stainless steel is recommended for any shear connectors.

Decorative concrete finishes were popular in the 1960s and 1970s. Some of these were effective in producing a pleasing appearance, but many were not. Designers thinking of using such an approach for a floodwall are strongly advised to examine existing walls to see what they look like after a long period of service.

Although steel is often the preferred material for sheetpiling, alternatives are now readily available including plastic (vinyl) and composites that do not suffer from corrosion. The most important design issues for sheetpiling are:

- strength for driving;
- durability;
- strength insitu;
- visual appearance;
- resistance to corrosion and other forms of deterioration;
- resistance to impact damage;
- cost.

It is common for flood defence schemes to make use of recycled steel sheetpiles, thereby reducing the overall environmental impact and saving cost.

9.7.3 Joints in floodwalls

Joints in concrete walls often cause problems for designers. These problems include:

- whether there should be reinforcement across the joint to resist differential settlement;
- whether a waterstop is needed;
- what type of joint filler to use;
- what type of joint sealer to use.

The answers depend on:

- the nature of the wall and its foundations;
- the relative movement to be accommodated.

It is not normal for the reinforcement to pass through the joint, but this may be appropriate if serious differential settlement is expected. It is preferable to reduce the risk of settlement by strengthening the foundation.

For low hydrostatic heads (say less than 1m), it is probably not necessary to have a waterstop in a floodwall. Use of an appropriate joint filler and joint sealer would keep seepage at an acceptably low level. For higher hydrostatic heads, the provision of a waterstop may be advisable to eliminate the risk of leakage through the wall.

Figure 9.7 Joint in concrete floodwall

The joint sealer in this joint has lost its elasticity and, as a result, has become separated from the wall on one side. If the joint incorporates a waterstop, the gap will not result in leakage through the defence. The sealant should be replaced to keep the movement joint free of debris.

If there is no waterstop in the joint, the gap between sealant and concrete will result in leakage in a flood. This would be disconcerting to local residents. In addition, the water may accumulate in a low area causing localised flooding if left unattended in a long duration flood.

Shrinkage of concrete occurs as it sets and dries out. This often results in the joint filler not filling the gap. This is not a serious problem provided that the joint sealer is effective. The joint sealer must have good adhesion to the concrete and sufficient elasticity to accommodate the anticipated movement (shrinkage, expansion, contraction, settlement). The advice of joint filler and sealer manufacturers should be sought when specifying the materials for any particular wall.

All joint sealers – and to a lesser extent joint filler and even waterstops – deteriorate with time, and eventually require replacement (see Figure 9.7). It is essential that the inspection and maintenance requirements of these elements are spelt out to the asset owner or manager at the time of the design, so that the necessary manpower and resources can be provided to keep the defence in a serviceable condition throughout its design life.

Where concrete floodwalls are clad with brick or stone, vertical movement joints should pass through the cladding and through any coping, to avoid damage due to any differential settlement. The visual impact of movement joints can be reduced by locating them at piers in the wall.

9.7.4 Steel sheetpiling walls

Guidance on the design of sheetpile walls is given in *Piling handbook* (Arcelor, 2005) and examples are given in Case studies 9.1 and 9.2. Particular issues with the use of steel sheetpiling for floodwalls include:

- corrosion, especially in saline water – special measures may need to be taken if the corrosion risk is high (Arcelor, 2005);
- driving conditions – hard driving through dense gravels or obstructions may require a much heavier duty pile than required for the performance of the flood defence;
- the advisability of avoiding cantilever sheetpiles except for the lowest of floodwalls (they tend to lean out over time);
- the design of tie rods to resist corrosion and to accept settlement of the backfill behind the wall;
- the risk of erosion of the riverbed in front of the wall, reducing the restraining forces in the foundation.

The appearance of steel sheetpile walling can be stark, although on a working quayside it may be appropriate to the setting without the need for cladding. There is little point in painting exposed sheetpile walls, especially in a tidal environment. Corrosion must be anticipated, allowed for in the design, and accepted. Designers please note – painting a sheetpile wall green does not reduce its visual impact!

9.7.5 Provision for access through floodwalls

It is often necessary to provide access ways through a flood defence to allow people and, in some cases, vehicles to pass through. There are several ways of ensuring that these gaps can be closed when flood conditions are developing. Most often this takes the form of a gate (see Figure 9.8), but stoplogs may also be appropriate. An important factor is the need to establish responsibility for timely closure of the gap so that the proper functioning of the flood defence is not compromised.

Figure 9.8 Gates to provide road access

In this case the flood defence is interrupted by a road in a situation where ramping up the road to pass over the defence was impractical.

The gate comprises two side-hinged leaves that close together in a similar manner to lock gates, ensuring that the pressure of the floodwater forces the gates together to effect a good seal.

Note also the built-in steel members in the road to form a sound surface for the bottom seals on the gates.

In the case of a removable defence (as illustrated in Figure 9.9), it is also essential that the removable components are securely stored nearby so that they can be mobilised at short notice and there is no risk of them being lost.

Figure 9.9 Removable defence in a floodwall in Cambridge

This access way is closed with stoplogs when flood conditions in the River Cam are anticipated. Sealing between the stoplogs is difficult and it is prudent in such situations to construct a small sump to allow pumping of any water that leaks through the defence.

This defence differs from a demountable defence in that it is intended only to close a small gap in a permanent defence, whereas a demountable defence is an alternative to a permanent defence where the latter is unacceptable (for visual amenity or access reasons, for example) – see Section 9.10.

9.8 Flood embankments

Flood embankments are earthfill structures designed to contain high river levels. They are commonly grass-covered, but may need additional protection against erosion by swiftly flowing water, waves or overtopping. Protection may take many forms, but options include:

- stone riprap;
- gabions and gabion mattresses;
- open-stone asphalt;
- concrete bagwork;
- concrete blockwork (which can either be individual blocks or linked to form a mattress);
- various products that may be categorised as bioengineering such as coir rolls, faggots and fascine mattresses.

Geogrids and geotextiles can also be used to reinforce grass on flood embankments.

The basic form of a flood embankment is trapezoidal in cross section (see Figure 9.4), with a horizontal crest and sloping inner and outer faces.

The width of the crest is normally determined by asset management requirements, with widths of 2m to 5m being the normal range. In the absence of more specific guidance, designers are advised to adopt a crest width which is two metres wider than the maximum width of plant that will be used on the crest (allowing one metre safety margin on each side).

The slopes of the inner and outer faces are a function of:

- the strength characteristics of the earthfill material used;
- the type of maintenance equipment used (for grass cutting, for example);
- any landscaping requirements.

Normally the embankment side slopes are between 1:2 (vertical to horizontal) and 1:3. Steeper slopes are very difficult to maintain (grass cutting), while flatter slopes tend to add unnecessarily to the footprint of the embankment and the quantity of fill material required.

An embankment with relatively steep face slopes has a smaller footprint and lower earthfill requirement than one with more gentle slopes; it may therefore cost less and have a lower environmental impact. Steeper slopes can be achieved by using earthfill with a higher clay content or by a range of soil strengthening techniques, but designers must always take into account the asset management needs and ensure that these can be carried out safely (for example, avoiding the risk of maintenance plant overturning on a steep slope). The designer must be certain that the profile of the embankment selected meets all the service requirements and, in particular, is stable throughout the full range of loading conditions.

General guidance on flood embankments can be found in *Management of flood embankments – good practice review* (Defra and Environment Agency, 2007). An example is shown in Case study 9.3.

Guidance on the environmental and landscaping aspects of flood embankments can be found in Chapter 5 of this guide and in the Environment Agency's *Landscape and environmental design guide* (Environment Agency, 2007).

Embankments are normally set back from the edge of the river to:

- allow for some flood storage on the floodplain;
- reduce the risk of undermining caused by riverbank erosion.

Set-back embankments are also less prone to erosion of the riverward face due to high velocity flow, but may be more prone to wave damage.

Flood embankments can be constructed from a variety of earth materials. Wherever possible, locally won material should be used, to reduce costs and lessen the environmental impact. The strength of the material used to construct the embankment is increased by compaction, which is a fundamental part of the construction process. The required strength is achieved by constructing the embankment in layers and compacting each layer using mechanical plant appropriate to the type of soil. It may be necessary to add water to each layer to improve the degree of compaction required; this depends on the nature of the soil and its moisture content. The advice of a geotechnical engineer should be sought regarding the appropriate layer thickness and the type of compaction plant required.

Soils with high clay content are best avoided because these crack when they dry out, and such cracks can extend a metre or more into the bank, compromising its function as a flood defence. Soils with a high sand or gravel content can be used, but may have to incorporate some form of cutoff to reduce seepage in flood conditions. Granular soils are less resistant to erosion than cohesive soils once the topsoil layer has been eroded.

Because of the shortage of suitable fill and the adverse environmental consequences of importing large quantities of fill from afar, various alternatives to conventional fill material have been explored. These include the use of recycled tyres compressed into bales to form a central core to a flood embankment. Options such as this need careful investigation before being adopted, with particular emphasis being given to long term durability and stability, environmental risks (such as contamination) and the overall environmental impact.

It is normal to strip topsoil from the foundation of an embankment before construction starts. This helps to key the embankment to its foundation and reduces settlement. It also provides a source of topsoil to encase the embankment and allow the establishment of a suitable grass cover.

Where the foundation soils are weak (for example, a layer of peat), the options are:

- remove the weak layer (if it is near the surface and relatively thin);
- strengthen the foundation (potentially an expensive option);
- accept and allow for the resulting long-term settlement;
- pre-load the foundation to accelerate settlement.

If the foundation is highly permeable (for example, a thick layer of gravel), it may be necessary to take steps to cut off the seepage path through the foundation.

Embankment foundations should always be checked for the presence of buried (agricultural) land drains prior to construction, as any that are left in place could result in excessive seepage and even embankment failure.

Other services may also be present along the route of the flood embankment, and these may need to be diverted or protected to avoid damage. The cost of diverting a gas or water main can be significant, but is normally much less than the costs from accidental damage during construction of the embankment!

Embankments in rural settings are often accessible by livestock and agricultural machinery. Both can cause significant damage, degrading the bank crest where they regularly congregate or cross the defence. Fencing can be used to control livestock movement, and pathways and machine access routes can be surfaced to reduce the likelihood and amount of damage. Cattle can be prevented from grazing flood embankments by providing two strands of barbed wire at the top of fence posts. The height of the lower strand can be high enough to allow sheep to pass under, as sheep do not cause damage to the embankment surface. Stock-proof fencing may be required at field boundaries. Gates or stiles may be required to maintain pedestrian access.

If a high level of burrowing damage is expected, it may be appropriate to incorporate a deterrent (such as wire netting) into the surfaces of the embankment.

Cracks in embankments can create seepage paths. Cracking occurs in clay soils during dry conditions and is best avoided by not using highly plastic clay soils for fill in the top metre of the crest.

Seepage can also occur where structures pass through the embankment (for example, a drainage culvert). The soil–structure interface requires careful attention during construction to minimise this risk, most notably by ensuring good compaction of the embankment fill around the structure. The likelihood of seepage can also be reduced by lengthening the seepage path (for example, by constructing a concrete collar round a pipe passing through the embankment).

Figure 9.10 shows a floodbank with a crest wall and Figure 9.11 a flood embankment with a sheetpile wall.

Figure 9.10 Floodbank with crest wall

The addition of the crest wall raises the height of the defence without increasing the footprint of the embankment. It also presents the opportunity to have a crest level that is not subject to erosion damage. However, the wall may restrict vehicular access along and across the bank, and it does detract from the visual amenity of the bank. It is vital to undertake a stability analysis to check the performance of the crest wall under extreme hydraulic loading.

Figure 9.11 Flood embankment with sheetpile wall

This flood embankment has a sheetpile wall driven through the crest. The advantages of this approach include:

- the sheetpiles can be driven deep enough to provide an effective cutoff;
- the presence of the sheetpiling allows the embankment to occupy a smaller footprint;
- the projecting sheetpiles provide additional height to the defence and form a consistently level and erosion-proof crest.

However, visual amenity considerations may discourage the use of this approach. It also has the disadvantage (in this case) of preventing vehicular access for inspection and maintenance.

Embankments offer good opportunities for landscaping flood defences into their surroundings. They do not have to follow straight lines, and can have variable crest widths and side slopes – provided the dimensions are appropriate for the materials used and do not compromise maintenance activities. Trees should not be planted on flood embankments as they accelerate drying out and cracking, and a breach of the bank may result if they are blown down in a storm.

Figure 9.12 River Trent floodbank in Nottingham

Note that the floodbank incorporates a surfaced path. This not only improves access along the river for members of the public, but also helps to define the crest level and makes its degradation less likely.

Flood embankments are often used as public footpaths, either informally or as designated rights of way (see Figure 9.12). Access ways along or across embankments may need surfacing to prevent degradation of the flood defence. Details are available for footpaths, steps and ramps from the Environment Agency's National Capital Programme Management Service (NCPMS) (see TD09, TD10 and TD13 on the NCPMS website).

9.9 Foundations

9.9.1 Foundation problems

Fluvial flood defences are often founded on alluvial deposits that can include sand, gravel, silt and clay. Compressible peat layers can also be present, making long-term settlement inevitable and limiting the overall bearing capacity of the foundation. Sand and gravel layers under a defence provide a route for seepage which, in extreme cases, can cause the defence to collapse. In such cases, the provision of a cutoff under the defence should be considered (see Sections 9.7 and 9.8). A cutoff can also help to resist sliding forces resulting from the differential hydrostatic pressure.

When accompanied by a high groundwater level, sand in the foundation may complicate the construction of the foundation for a floodwall. Running sand conditions cause the sides of excavations to collapse, requiring expensive dewatering systems or construction within a cofferdam, or both.

It is essential that an assessment of ground conditions is made as part of the process of choosing the alignment of a defence; further ground investigation may be necessary prior to finalising the design. For low height defences, trial pits may reveal sufficient information about the ground. For higher defences, or where the ground conditions are complex or variable, boreholes are likely to be required. Guidance on the requirements for site investigation can be found in BS 5930 *Code of practice for site investigations* (BSI, 1999). There is also guidance in BS EN 1997-2, Eurocode 7, *Ground investigation and testing*.

Even with a comprehensive site investigation, the variability of foundation conditions may cause problems during construction. The risk register should allow for this eventuality.

Constructing a floodwall on very weak foundations can lead to problems of differential settlement and cracking of the wall. Solutions include:

- removal of the weak material and replacement by suitable fill (or weak concrete);
- grouting;
- adoption of a wide foundation to the wall to reduce the bearing pressure.

In the case of a flood embankment on a weak foundation, the possibility of pre-loading the foundation may be considered. This involves temporarily constructing the embankment to a higher level, leaving it to allow consolidation to take place, then reforming the embankment to the desired level after a period of time.

The importance of the foundations for a wall or embankment, and the earthfill properties in the case of an embankment, make it essential that all flood defence structures undergo a stability analysis covering the full range of flood conditions. The strength parameters of soils are variable and difficult to establish accurately. It is therefore important that:

- realistic parameter values are adopted for stability analysis;
- sensitivity tests are carried out to examine the impact of changes in parameter values.

Guidance can be found in *Smith's elements of soil mechanics* (Smith, 2006) and in BS EN 1997 Eurocode 7, *Geotechnical design* (BSI, 2004, 2007).

9.9.2 Seepage under or through a defence

Most flood defences are constructed on foundations that are permeable to some degree. This means there will be some seepage under the defence when the defence is under hydraulic loading (that is, when the water level on the river side is higher than on the defended side). In the case of a flood embankment, there may also be seepage through the defence.

The seepage can range from an inconsequential damp patch on the landward side of the defence to complete failure of the defence due to piping. The hydraulic forces that drive seepage also result in uplift pressures on the underside of a flood defence structure. This must be taken into account when assessing the stability of a floodwall.

A cutoff is used where the seepage under the defence would be unacceptable, either because the seepage water would itself create a flooding or nuisance problem, or because it could destabilise the wall or embankment as a result of water pressures or the erosion of foundation material.

Figures 9.13 and 9.14 illustrate the concepts of seepage, uplift and piping in the context of a floodwall with and without a cutoff. The pressure and seepage under the wall are illustrated by the flow-net, which is made up of the equipotential lines (lines of equal pressure) and the flow lines that represent the direction of seepage flow; note how the pressure drops as the seepage flow passes under the structure. The rate of drop in pressure represents the hydraulic gradient. A high hydraulic gradient on the landward side of the wall (the exit gradient) is an indicator of the potential for piping, which could lead to loss of strength in the soil and failure of the wall. The provision of a cutoff can reduce the exit gradient and reduce the rate of seepage, but it can lead to increased uplift pressure on the base on the wall (as illustrated in Figure 9.14).

Even when cutoffs are provided, there may be some seepage through or under a flood defence. It is important to recognise this and to design the flood defence system to take this into account.

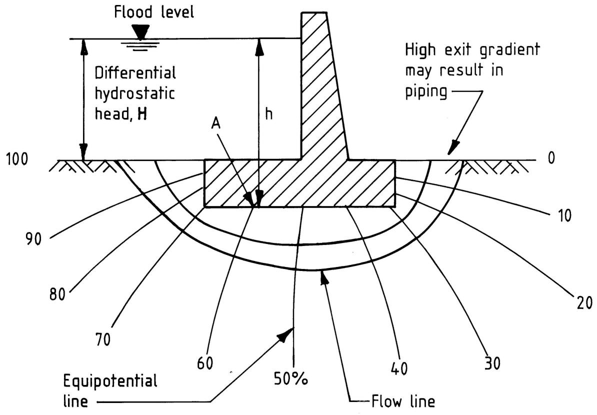


Figure 9.13 Uplift and seepage

This diagram represents the flow of water under a floodwall. The equipotential lines represent the drop in pressure and the flow lines represent the seepage paths. In this illustrative example, 30% of the differential hydrostatic head (*H*) is dissipated over the depth of the wall base on the landward side. This yields a high exit gradient and hence the potential for piping.

Note that the uplift pressure at Point A is calculated as ($h - 0.4H$). It is the hydrostatic head (*h*) less the dissipation of differential head (40% of *H*).

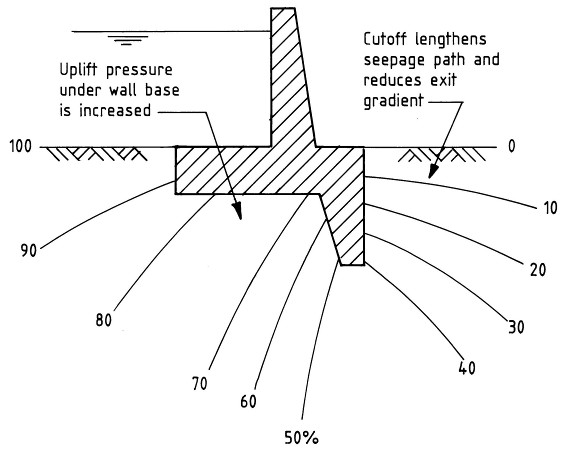


Figure 9.14 Effect of a cutoff

The cutoff (in this case positioned on the landward side of the wall) has two impacts:

- it increase the seepage path length and thus reduces the exit gradient (the rate of dissipation of head in the soil on the defended side), in this case to about half; but
- it also increases the uplift pressure under the base of the wall (which acts together with the horizontal hydrostatic force to overturn the wall).

The uplift pressure at point A is now about ($h - 0.2H$).

Seepage through and under embankments is not uncommon, but is generally only a serious problem if it is concentrated, for example due to holes caused by burrowing animals such as rabbits and badgers. The best way to avoid seepage through an embankment is to use relatively impermeable fill material, though this may not be available locally. The presence of seepage through existing defences can sometimes be highlighted by more lush vegetation, as well as by damp or boggy ground.

The best solution is often to provide a toe drain behind the defences. A gravel toe drain consists of several layers of graded aggregate, with the finest material at the soil interface, progressing to coarser material. Alternatively, the finer layer can be omitted and replaced by a geotextile filter fabric. The toe drain can also be an open drainage channel (this often occurs when fill material has been sourced from the land immediately behind the defence). The disadvantage of an open toe drain is that its presence can destabilise the embankment, particularly if the drain is close to the embankment. A high exit gradient is rarely a problem with embankments because the seepage path is long compared with that under a floodwall; but it is always wise to check, especially if an open drain is constructed at the toe of the embankment.

Provision must be made for the seepage to accumulate at suitable locations from which it can be pumped, if necessary, or will discharge by gravity after the flood has passed.

Concentrated local seepage needs further investigation to establish the cause. Potential solutions include reconstructing the defence locally, providing a local cutoff or grouting the foundations.

Many defences in urban areas leak through the foundation without causing problems other than the need for temporary pumping of seepage water during a flood event. Where the need for temporary pumping is recognised from the outset, the provision of a collector drain and strategically located sumps simplifies the deployment of pumps and the management of seepage.

9.9.3 Design of a cutoff

The design of the cutoff depends on:

- the type of defence;
- nature and depth of the permeable layer;
- cost of materials;
- access for construction.

Steel or plastic sheetpiling is one of the most common forms of cutoff and can be used in conjunction with either floodwalls or embankments. Sheetpiling is not watertight, but is generally capable of reducing seepage to an acceptable amount. Concrete cutoffs can also be used under walls, although excavation for their construction may be complicated by the presence of running sand. In this case, the sheetpiling alternative offers considerable advantages. An example is given in Case study 9.4.

One possible option to be considered in urban areas is the use of steel sheetpiling to form both the floodwall and the cutoff (see Figure 9.17). The sheetpiling can be clad in brickwork or masonry, but the structural integrity is largely provided by the piling. The presence of buried drains, services or other obstructions may complicate pile-driving or even make it impracticable. Thorough site investigation and service enquiries in the early stages of design development should identify any buried equipment that might make pile driving hazardous or impractical. The use of sheetpiling may be complicated by restricted access for the piling machinery and by proximity to sensitive buildings, although these days there are many different sizes and types of piling rig to meet most circumstances.

Under embankments, the use of a clay cutoff is another option, but this becomes uneconomic or impractical where the depth of the permeable layer exceeds about 2m, or where there is no suitable source of clay nearby. Bentonite trenches have been used to provide a cutoff through deeper permeable layers.

In the case of existing walls or embankments that are suffering from seepage problems, it is likely that practicality issues will determine the nature of the appropriate solution.

- Grouting is only effective in certain types of soil and may have unwanted environmental impacts close to a river or stream.
- Sheetpiling can solve the problem in an embankment, but is likely to be expensive if the permeable layer is deep.

9.10 Temporary and demountable defences

9.10.1 Definitions

A **temporary** flood barrier is one that is only installed when the need arises (that is, when high flood levels are forecast).

A **demountable** flood defence is a particular form of temporary defence that requires built-in parts and therefore can only be deployed in one specific location. The removable stoplog defence shown in Figure 9.8 is a particular form of demountable defence applicable only for small openings in a permanent defence. The more commonly adopted gate option for closing off a gap in a floodwall is neither temporary nor demountable, as it is part of the permanent defence and is left in place all the time (albeit normally in an open position).

Both temporary and demountable defences require a considerable amount of pre-planning to ensure that they can provide an effective defence. It is essential that the operational resources, storage facilities and the logistics of deployment are fully appreciated by anyone planning to rely on these types of defence.

9.10.2 Temporary flood barriers

There are many forms of temporary flood barrier, ranging from sandbags to the so-called pallet barrier. These are suitable for deployment in response to a developing flood in situations where there are no permanent defences or where the existing defences are not high enough.

Sandbags can be used to provide a degree of protection at the entrances to individual properties. They have also been used successfully to raise the crest level of significant lengths of flood embankment. However, sandbags do not provide a watertight defence and are practical only up to a height of about 0.3m, perhaps 0.5m in ideal circumstances. They require considerable effort to deploy and often prove ineffective.

The **pallet barrier** is a more sophisticated system which is deployable over a length of several hundred metres. It consists of a lightweight structural system which supports an impermeable membrane. The system relies on a reasonably firm and level foundation. The effective use of such systems also depends on the ability to mobilise them fairly quickly in response to a growing threat of flooding. Storage of the necessary equipment reasonably close to the site is therefore essential, otherwise there is a risk that the defence will not be delivered to site and erected in time to prevent flooding (see also the guidance below on demountable defences in this regard).

Whereas temporary barriers may seem to offer a viable solution in situations where there is sufficient time to mobilise and erect them, such systems have other potential disadvantages. It is essential to ensure that no significant drains or other flow pathways are present that would compromise the effectiveness of the defence. There are also likely to be issues with parked cars and road closures that may delay the deployment of the defence to the point where deployment is too late.

Temporary barriers therefore require a considerable amount of pre-planning to ensure that they can provide an effective defence. For any type of temporary defence, it is essential that the operational resources (labour, plant and equipment), storage facilities (access to and from, security, proximity to point of deployment), and the logistics of deployment are fully explored before the commitment to rely upon this approach is made.

9.10.3 Demountable flood defences

Demountable flood defences are used where a permanent defence is unacceptable, usually because of the visual intrusion and loss of amenity that a permanent defence would entail. These are relatively new to the UK, but have recently been successfully installed and operated in Shrewsbury and Bewdley on the River Severn (see Figures 9.15 and 9.16), and in parts of north Wales.

Time is the key factor concerning the adoption of demountable defences. There must be sufficient advance warning of a flood to allow the defence to be deployed. In addition, the advance warning must be reasonably reliable so as to avoid excessive precautionary deployment of the defences. They are therefore suitable on the middle and lower reaches of the River Severn, for example, where flood conditions can be predicted days in advance, then confirmed with plenty of time to mobilise the erection team.

More details of demountable defences can be found in Environment Agency R&D Publication 130 (Ogunyoye and van Heereveld, 2002).

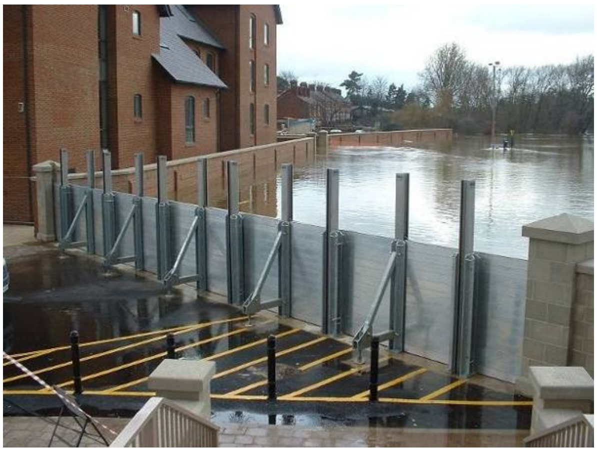


Figure 9.15 Frankwell flood alleviation scheme, Shrewsbury (River Severn)

First deployment of the defences in the flood of February 2004, at the peak of which 1.9m depth of floodwater was held back, preventing the flooding of up to 74 properties.

The key feature of a demountable defence is the provision of built-in sockets or similar foundations that the demountable supports slot into. There may also be built-in provision for struts to lend additional support to the defence.

Figure 9.16 A demountable defence being erected at Bewdley (River Severn)

It is easy to see why a permanent floodwall in this location would not be acceptable to the local residents – its height would obscure the view of the river from the waterfront and the residences, and would restrict access.

The use of a demountable defence means that the residents can enjoy the view and have flood defence, but such win–win solutions are only suitable in certain situations.

Demountable defences may make use of standard panels, but they often have to be custom-designed to suit a particular location. They rely on built-in foundations for stability and ease of erection.

The components of the demountable defence must be stored relatively near to the site to reduce the risk of delays once the decision to mobilise has been made. A skilled erection team is required to ensure that the defence can be safely and securely erected in the limited time available. For practical reasons, the length of a demountable defence is unlikely to exceed a few hundred metres.

Whereas demountable defences may seem to offer the ideal solution where visual impact is a key factor, this form of defence tends to be expensive and there will always be a risk that the defence elements are not deployed in time to avert flooding. Theft of defence units, damage to built-in parts and delays in transporting the units to site can all conspire to make deployment problematic.

In July 2007, the delivery of the components of a demountable defence at Upton-on-Severn was delayed due to the severe disruption to the transport infrastructure caused by surface water flooding. The defence was not deployed in time and there was considerable flood damage as a result. In fact, had these demountable defences been deployed, they would have been overtopped due to the severity of the flood, but this example illustrates just how important it is to make sure that these defences can be successfully deployed in a flood event.

9.11 Visual aspects of floodwalls and flood embankments

Rivers are a major feature of many towns and landscapes, providing both a physical and a visual amenity. Permanent flood defences, by their nature, form a barrier between the river and the protected area. Although this barrier against rising river levels is generally welcomed, it may also have undesirable effects including cutting off a view of the river, and restricting pedestrian, vehicle and animal access.

To some extent, this can be overcome by providing openings in the defence that can be closed off in times of flood. Generally the openings have small gates, allowing pedestrian access, with wider gates for vehicles. Figure 9.17 shows an example of a small gate in a floodwall for pedestrian access in Boroughbridge in north Yorkshire on the River Ure.

Steps should be avoided where practicable, so as to allow full access to disabled people. Where space permits, disabled access can be provided by ramps that pass over the defence. Large openings in a defence that are provided in the interests of visual amenity require the use of demountable defences (see Section 9.10). All these issues should be explored as part of the environmental impact assessment (see Chapters 1, 3, 4 and 5).

Figure 9.17 Floodgate in a brick-clad sheetpile floodwall, Boroughbridge (Yorkshire)

This floodwall is constructed from steel sheetpiling with brick cladding. Steel sheetpiling was used because it could provide a cutoff through the permeable gravel foundation as well as providing the structural element of the wall. Setting back a portion of the floodwall has created a more visually interesting wall and helps to make the floodgates less prominent.

Note that the brickwork is not structural (the stability of the wall relies on the sheetpiling alone). The coping stones enhance the appearance of the wall, but their height was not included in the design level of the defence. Therefore loss of one or more coping stones would not compromise the design standard of the flood defence.

Approval of the cladding design is likely to be a condition of the planning consent for this sort of project.

In all cases, the responsibility for closure of gaps in defences must be established in advance and measures put in place to ensure that all gaps are securely closed in flood conditions.

Floodwalls and embankments placed on public land close to houses may raise issues of privacy and security by giving high level access to pedestrians. There may also be safety issues to consider if high walls are proposed in areas where children are likely to play.

In situations where a riverside floodwall is the only practicable means of providing flood defence to a significant urban area, the need to protect a large number of residents may have to take precedence over the views of those living immediately alongside the river. The visual and physical impact of riverside walls should not be underestimated, and the negative impacts do not affect only those living in the immediate vicinity. Every attempt should be made to create a defence that enhances the environment without compromising the primary function of flood alleviation (see Figure 9.18).

Having decided that a floodwall is the appropriate solution, it is necessary to investigate its visual appearance, form and layout, and alignment. Often it is appropriate to clad or treat a wall surface in some way to integrate it into the surroundings (see Figure 9.17). Landscape character assessment can help to determine the appropriate type of finish. Advice notes LVIA 1 and 2 (*Landscape and visual assessment*) issued with *Landscape and environmental design guide* (LEDG) (Environment Agency, 2007) give more information on the use of landscape character assessment. LEDG advice notes F3 and

F4 give guidance on finishes and cladding. An example of a floodwall in a 'heritage' setting is given in Case study 9.5.

The form and layout of a wall needs consideration and in particular how the new wall relates to existing walls or how changes in height of the floodwall are handled. Piers and columns can help to add interest to a design and overcome difficult transitions. See LEDG advice notes F1 and F2.

Figure 9.18 Is it a floodwall?

The secret of successful integration is to create a floodwall that does not look like a floodwall.

To the casual observer this wall would probably appear simply as a wall defining a boundary. The use of attractive coping stones and handrailing, and the sturdy pier at the corner, add to the visual attractiveness and public safety without compromising the flood defence function.

But such well-disguised defences may require some form of marking as a warning of their purpose (see Box 9.2).

Box 9.2 Disguising flood defences

Where a floodwall is deliberately 'disguised' to help it to blend into the local environment, it may be appropriate to provide some form of marking to warn landowners, utility companies and others that it is a flood defence, and that any damage to it could compromise the effectiveness of the defence. This is particularly important where the flood defence is disguised as a boundary wall.

Consideration also needs to be given to the alignment of floodwalls and embankments. Careful routing of walls and embankments can avoid damaging important habitats and, in particular, preserve mature trees. Specialist advice should be sought when constructing close to trees, as the excavations are likely to have a considerable impact on the stability and life expectancy of mature trees. See LEDG advice note T4 for advice on protecting trees. Figure 9.19 shows an example of good practice.

Trees close to a flood defence can result in damage to the defence as a result of moisture removal by the roots and consequent settlement of the defence. Trees should not be planted on flood embankments, as they accelerate drying out and cracking, and a breach of the bank may result if they are blown down in a storm.

Figure 9.19 Precast block floodwall

At Walton le Dale, precast mass concrete blocks were used. These required limited foundations and therefore had little impact where the wall had to run close to mature trees. The blocks were pigmented and acid-etched to give the appearance of natural stone.

Note the inclusion of a railing on the defence to improve the safety of pedestrians using the adjacent footpath.

Artwork can also be incorporated into walls (see LEDG advice note F4). For example, schoolchildren working with a local artist have made bricks to form part of the Northampton flood defences and panels in the Nottingham flood defences.

Very high floodwalls can be visually intrusive and intimidating. One possible option is to terrace the floodwall (see Box 9.3).

If the coping stones on top of a wall are to form part of the defence (that is, if the defence level is the top of the coping), then the stones must be fixed securely to the wall so that they cannot be accidentally or deliberately dislodged or removed. Some designers prefer to exclude the coping from consideration of the defence level, so that the loss of one or more coping stones would not reduce the standard of defence. However, the additional height of the wall then adds to its cost and visual impact. And, if stones are easily removed, the visual amenity of the wall could be impaired.

Low walls can present a trip hazard with a significant fall on the other side, sometimes straight into a river. The solution may be to heighten the wall above the level required for flood defence or to add railings. Consideration of these issues in the design development stage is essential. Railings added at a later date cost more and usually look like an afterthought, detracting from an otherwise well designed wall (see LEDG advice note F5).

Steeply ridged capping or coping stones help to discourage children from walking on the crest of the wall and exposing themselves to a fall hazard, but such solutions are not effective or appropriate in all situations.

Figure 9.20 shows an imaginative solution to the problem of visual impact from Kings Lynn.

Figure 9.20 Kings Lynn flood defences

An imaginative solution in which elements of the flood defence fold down to form seats when not in use. This reduces the visual impact of the floodwall and allows for the incorporation of an attractive feature on the waterfront.

Like the flood gate in Figure 9.17, this defence is not removable (and is therefore much less prone to acts of vandalism). But in this case responsibility for closure rests with the local authority.

Embankments are perhaps easier to incorporate into the landscape than walls, but they have their own problems. Trees cannot generally be planted on flood embankments because they present a risk of damaging the structure of the bank.

In cases where trees would provide a significant visual or ecological enhancement, it is possible to over-widen a bank or provide a sheetpile cutoff through the bank to allow limited planting of trees. This option requires approval at the time of design of the flood embankment to:

- ensure there was no risk of damage to the flood defence as the trees grow;
- avoid making maintenance of the embankment unduly difficult.

Wildflowers can be encouraged to grow on embankments. However, special mixes and seeding rates are needed to ensure successful establishment (see LEDG advice note E5).

The environmental impact of the construction of a flood embankment is often reduced if the earthfill material needed is obtained locally (avoiding costly and damaging transportation of large quantities of earth). Excavation of the earth also creates the opportunity for enhancement of the borrow pit for nature conservation or amenity use. Locating the borrow pit very close to the embankment can increase the risk of seepage and destabilise the bank, so this option requires a full geotechnical appraisal to ensure that the defence remains safe in flood conditions.

Flood embankments can be varied in height and profile to make them look less like a structure or more like part of the natural landscape (see Figure 9.21). However, there is a risk in making a defence too 'invisible', in that landowners may fail to recognise it as such and damage it in some way. Damage should be picked up by the Environment Agency's flood defence asset inspectors during their routine inspections, but it is best to avoid it in the first place. One way to achieve this is to incorporate discrete but visible concrete markers at intervals, which carry a clear message that the bank is a designated flood defence.

Figure 9.21 Aylesbury flood defences

Wherever possible a flood defence embankment should blend in to its surroundings, although it should generally remain obvious that it is a flood defence so as to avoid the risk of it being compromised at some time in the future.

9.12 Construction of floodwalls and embankments

To avoid difficult or inherently unsafe construction practices, designers of flood defence works must consider not only the function(s) of the structures but also the construction process. This applies to all civil engineering works, but can be a particular issue for flood defences because of the nature of the environment in which construction takes place.

Flood defences often have to be constructed in limited space, and close to homes and places of work. Householders often do not appreciate the extent to which construction works will impact on them. Even a superficially small wall constructed in a garden can have a major local impact. It is therefore important to:

- discuss the proposed work in detail with the people affected well in advance;
- ensure that the works are constructed with minimum land take and, where appropriate, in a staged manner.

Construction of floodwalls and embankments may interfere with the use of public footpaths alongside rivers and streams. Diversion or temporary closure of the path may be required, which requires the consent of the local authority and advance notice.

Temporary works and the sequence of construction for both new and raised defences must be planned so that the risks of damage are not increased in the event of a flood during construction. This often requires the works to be constructed in a particular sequence to maintain the continuity of the defence. There should also be a plan of action for dealing with a flood emergency.

High river levels during construction can severely impact upon the construction process (see Box 9.3), making access difficult and turning foundations into a quagmire. Timing the works to avoid the winter months may help, but often this means more interference with public use of the riverside. Detailed knowledge of the hydrology of the river and its use for amenity and recreation should allow the selection of the most appropriate construction period.

Box 9.3 Successful construction project

Riverside property flooded before the construction of flood defences

Note the height of the water compared with the normal water level illustrated in the photograph below. It is easy to see how high river levels during construction of the flood defence would impact upon the construction process.

The photograph below shows the situation now that a floodwall has been constructed.

After construction of a floodwall

Note the scale of the floodwall and the way in which it has been tiered to break up what would otherwise have been a massive structure. Planting has been introduced between the two parts of the wall and the riverside walk has been improved. Thus flood defence has been achieved hand-in-hand with improvements to the amenity of the river frontage. However, such schemes are expensive and the wall obstructs the view of the river from the defended area. Planting schemes must be maintained to avoid them becoming an eyesore.

Access to the construction site may also be a constraint on construction, particularly in urban areas, but also in rural settings where the environmental impact may be significant. An example could be the need to import large quantities of earthfill material through the countryside. In such circumstances, the designer should seek to reduce the impact by examining alternative designs. For example, the impact of importing large quantities of earthfill could be reduced if a smaller cross section were adopted for a flood embankment. This could be achieved by adopting reinforced soil techniques to allow steeper face slopes, with the additional benefit that the embankment footprint would be reduced. However, the implications for maintenance of the embankment also need to be considered (see Section 9.13).

In the case of flood embankments, the effectiveness of the defence depends greatly on the selection of appropriate fill material and the placing and compaction of the fill to form the embankment. However, ideal fill material is rarely available locally, so it may necessary to compromise, in which case control over placing and compaction becomes even more important. A poorly compacted embankment will settle over time and may leak excessively when subjected to hydrostatic loading. It will also be less resistant to erosion by flowing water and to damage by trafficking.

The potential adverse impacts of construction can also include noise and vibration (for example, pile driving) and pollution of watercourses or groundwater (for example, grouting of foundations). The designer can address these at the time of the design by adopting alternative approaches, or by specifying certain types of plant or materials that reduce or eliminate the problem (for example, 'silent' pile driving techniques). In the case of the piled floodwall illustrated in Figure 9.17, concerns were raised about the impact of noise and vibration from the driving of sheetpiles so close to a residential building. Use of appropriate pile driving equipment overcame these concerns, but the compaction of a nearby reach of flood embankment using a vibrating roller caused disconcerting vibrations within the building and it was necessary to modify the construction method to reduce this adverse impact.

9.13 Maintenance of floodwalls and flood embankments

Designers should never forget that maintenance is a design issue and not something that is addressed after the design has been completed, or worse still overlooked altogether.

Failure to address maintenance requirements as part of the design can lead to unsafe and expensive asset management activities, and may result in the structure failing to perform its design function(s). The design of any flood defence structure should therefore include, as an output to be passed to the responsible party, clear definition of the inspection, monitoring and maintenance requirements for the structure. The monitoring and inspection requirements should stem from a clear understanding of the possible failure modes of the structure, so that the management of flood defences can be performance-based.

The biggest issue for maintenance is often **access**. Wherever possible, flood embankments should allow safe vehicular access for inspection and maintenance activities. Where space permits, it is usually preferable to place vehicular access at the base of the flood embankment rather than along the crest, to avoid the possibility of vehicles running off the crest and overturning. Such an access road can also be used in the construction process as a haul road.

Where it is necessary to provide access on the crest of the bank, the minimum crest width should be 3m and the edges of the bank should be clearly marked. Where frequent vehicular movements are to take place, the bank crest should be at least 4m wide.

It is vital that the designers of flood embankments consult the operations delivery team (that is, those people responsible for maintaining the bank) to agree safe **dimensions** for the crest and side slopes. Unsafe dimensions are very difficult to correct after construction. For example, for safe grass cutting of an embankment crest, the current recommendation is that the crest width is 2m wider than the grass cutting machine that will be used (that is, a one-metre clearance each side) (see GN02 – *Flood embankments*).

There should also be appropriately spaced access ramps to the crest that allow plant to turn on the crest. Depending on the spacing of ramps, there may be the need to incorporate intermediate turning points. **Turning points** are also needed at the ends of the defence whether or not a ramp is provided at the end.

At the time of design, it is important to define a suitable **inspection and maintenance regime,** tailored to the nature of the floodwall or embankment. For grass surfaces, for example, this should include keeping the grass trimmed.

- This improves the quality of the grass sward and the erosion protection that it provides.
- It reduces problems with weeds taking over (to the detriment of the grass cover) and reduces the cover provided for vermin.
- It increases the chances during routine inspections of detecting undue seepage, surface slips, embankment deformation and evidence of burrowing animals.

Flood embankments within or adjacent to farmland may often be conveniently grazed by small herbivores such as sheep, which maintain a short sward, normally without undue damage to the earth structure (sometimes the paths that sheep create can result in low spots on the crest of the bank).

Although floodwalls generally require much less maintenance than flood embankments, they must still have clear inspection and maintenance instructions to address maintenance issues which, if ignored or neglected, may lead to deterioration in the defence. The deterioration may compromise the effectiveness of the wall as a flood defence (for example, through the loss of joint sealer) or its appearance (for example, proliferation of graffiti or deterioration of planting schemes incorporated in the wall design).

Gates in floodwalls require regular attention to ensure they operate effectively in a flood event. Maintenance works include oiling of hinges and inspection of seals. The asset management regime should include at least one trial closure of each gate every year.

Built-in parts for demountable defences should be inspected and cleaned out regularly to ensure there are no delays to the erection procedure in a flood event.

Since the crest level of a flood defence is a fundamental aspect of its ability to perform its flood defence function, regular checks on crest level must be performed. More frequent checks are generally required for embankments than for walls, but the designer should initially define the checking frequency based on:

- the nature of the wall;
- the foundation conditions;
- likely traffic use (pedestrians, animals, vehicles).

In the case of a flood embankment, the designer should also define a minimum crest level which the asset manager must maintain in order to ensure that the defence meets its service level requirement.

The asset manager may refine the checking requirements during the service life of the defence, depending on the results of previous surveys.

Key references

Defra and Environment Agency (2007). *Management of flood embankments – a good practice review,* Technical Report FD2411/TR1. Environment Agency. Available from: http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD2411_6509_TRP.pdf.

This report from the joint Defra/Environment Agency flood and coastal erosion risk management R&D programme presents an overview of issues that can affect flood embankment performance and provides guidance on good practice for dealing with many aspects of design, operation (including inspection) and management (including adaptation). The guide has four main parts: A – Function and management of flood embankments; B – Performance and characterisation of flood embankments; C – Risk and risk management; and D – Good practice reference.

Kirby, A M and Ash, J R (2000). *Fluvial freeboard guidance note*, R&D Technical Report W187. Environment Agency. Available from: http://publications.environment-agency.gov.uk/pdf/STRW187-e-p.pdf.

This comprehensive guide is now perhaps a little out-of-date but is the most up-to-date guide on the subject. Some of the content is a little academic but if you want to know the full story of freeboard – this is it! It defines all the elements of freeboard and presents details of how to estimate appropriate values for each.

Ogunyoye, F and van Heereveld, M (2002). *Temporary and demountable flood protection: interim guidance on use,* R&D Publication 130/1. Environment Agency. Available from: http://sciencesearch.defra.gov.uk/Document.aspx?Document=TDFD_phase_1__1628.PDF.

This report presents the output of a detailed research project under the joint Defra/Environment Agency flood and coastal erosion risk management R&D programme into the pros and cons of temporary and demountable defences and their appropriateness for use in England and Wales. It covers the subject from the preliminary planning to installation and operation, and has outline details of a range of alternative systems.

Other references

Arcelor (2005). *Piling handbook,* 8th edition (revised 2008). Arcelor RPS UK Ltd (Scunthorpe). Available from: http://www.arcelormittal.com/sheetpiling/page/index/name/arcelor-piling-handbook.

British Standards Institution (1999). BS 5930: 1999 *Code of practice for site investigations.* BSI (incorporating Amendment N° 1, 2007).

British Standards Institution (2004). *BS EN 1997-1: 2004 Eurocode 7. Geotechnical design. General rules.* BSI.

British Standards Institution (2007). *BS EN 1997-2: 2007 Eurocode 7. Geotechnical design. Ground investigation and testing.* BSI.

Department for Environment, Food and Rural Affairs (2005). *Making space for water. Taking forward a new Government strategy for flood and coastal erosion risk management in England. First Government response to the autumn 2004 'Making space for water' exercise.* Defra. Available from: http://www.defra.gov.uk/environ/fcd/policy/strategy/firstresponse.pdf.

Department for Environment, Food and Rural Affairs (2006). *Project appraisal guidance: procedural guidance for operating authorities. Treatment of climate change impacts.* Defra. Available from: http://www.defra.gov.uk/environ/fcd/pubs/pagn/default.htm.

Environment Agency (2007). *National Environmental Assessment Service (NEAS) operational guidance. Volume 3: Landscape and environmental design guidance*. Environment Agency. Environment Agency internal document (details of accessibility to be established by web editor).
LEDG advice notes:

E5	*Establishing vegetation on flood embankments*
F1	*Summary of design principles and introduction to flood wall design*
F2	*Flood wall design and alignment*
F3	*Materials and finishes*
F4	*Cladding materials*
F5	*Cope stones and railings*
LVIA 1	*Landscape character assessment and visual impact assessment:* Part 1 – Introduction
LVIA 2	*Landscape character assessment and visual impact assessment:* Part 2 – Procedures
T4	*Protecting existing trees during construction*

Morris, M, Bramley, M and Smith, P (2004). *Good practice in design and management of flood embankments.* Proceedings of the 39th Defra Flood & Coastal Management Conference, 2004. Defra Publications, London – Product code PB10411.

Smith, I (2006). *Smith's elements of soil mechanics*, 8th edition. Blackwell Publishing.

GN02 *Flood embankments*