1

Dams and Their Components

1.1 Classification of Dams

A dam is a barrier that impounds water. Dams have been an essential infrastructure in society that contributes to socioeconomic development and prosperity. They are built for a number of purposes, including flood control, irrigation, hydropower, water supply, and recreation. Dams can be classified in many ways, depending on their size, materials, structural types, construction methods, etc. According to the definition of the International Commission on Large Dams (ICOLD, 1998a), a reference dam height for distinguishing large dams from small dams is 15 m. Based on the materials used, dams can be classified as earthfill or rockfill dams, concrete dams, masonry dams, cemented sand and gravel dams, and others. Dams of earthfill or rockfill materials are generally called embankment dams. Based on the structural types adopted, dams can be divided into gravity dams, arch dams, buttress dams, and others. Very often dams are constructed with a combination of two or more structural forms or materials. Of the various types of dam, embankment dams are the most common.

ICOLD (1998) has published a world register of dams, which gives some facts regarding the numbers of different types of dam throughout the world. There are 25,410 dams over 15 m high, of which 12,000 were built for irrigation, 6500 for hydropower and 5500 for water supply, although many of them serve more than one purpose. Embankment dams of earthfill predominate over the others, comprising about 64% of all reported dams, while those of rockfill comprise 8%. Masonry or concrete gravity dams represent 19%, arch dams 4%, and buttress dams 1.4%. Dams lower than 30 m form 62% of the reported dams, while those lower than 60 m comprise 90% and those higher than 100 m just over 2% of the total number of dams.

Topography and geology are the two primary factors in weighing the merits of dam types. These interrelated characteristics of the dam site influence the loading distribution on the foundation and the seepage patterns through the reservoir margins. Embankment dams can be built on a variety of foundations, ranging from weak deposits to strong rocks, which is one of the most important reasons for their wide use in the world. A dam project usually comprises several components, including a water-retaining structure (e.g. the dam), a water-releasing structure (e.g. the spillway), a water-conveying structure (e.g. conduits), and others (e.g. power plants). In addition to the main

structure of the dam, there are appurtenant structures such as the spillway, conduit, and power plant around a dam that are necessary for the operation of the whole dam system. Failures of, or accidents involving dams may be attributed to defects in either the dams themselves or their appurtenant structures.

Landslide dams are natural dams caused by rapid deposition of landslides, debris flows, or rock-fall materials. The formation of most landslide dams is trigged by rainfall or earthquakes. Earthquake is the most important cause. For instance, the Wenchuan earthquake in 2008 triggered 257 sizable landslide dams. Landslide dams and constructed embankment dams are similar in materials but different in geometry, soil components, and soil parameters. The differences largely influence the failure modes and breaching mechanisms of these two types of dam.

Dikes are a special type of dam. Although the height of a dike is typically small compared with that of a dam, a dike often protects a significant worth of property. Hence the failure statistics and mechanisms of dikes are also introduced in this book.

Here in Chapter 1, the structures of constructed embankment dams, natural landslide dams, concrete gravity dams, concrete arch dams, and dikes are introduced briefly.

1.2   Constructed Embankment Dams

Commonly constructed embankment dams can be divided into homogeneous dams, earth and rockfill dams with cores, and concrete-faced rockfill dams. A homogeneous dam (Figure 1.1) consists mainly of one single type of material. Such a dam is often constructed for soil and water conservation purposes, and many dams can be constructed along a gully in which soil erosion is serious. A conduit or other type of water passage facility may be installed inside a homogeneous dam. The interface between the conduit and the surrounding soils may easily become a channel of concentrated leak erosion.

An embankment dam can be constructed with earthfill or rockfill. Any dam which relies on fragmented rock materials as a major structural element is called a rockfill dam (Singh and Varshney, 1995). High quality rockfill is ideal for high-rise dams because it provides high shear strength and good drainage. A rockfill dam often has a vertical earth core or inclined earth core for seepage control. When a vertical core is adopted, the dam is zoned, with rockfill zones on both sides, a low-permeability zone (i.e. the earth core) in the middle, and transition and filter zones in between the core and the rockfill zones (Figure 1.2). The filters protect the earth core from internal erosion. They must be much more permeable than the core material and not be clogged by particles migrated from the core. The function of the transition zones is to coordinate the deformations of the core and the rockfill to minimize the stress arch effect and differential settlements.

Figure 1.2 shows a typical section of the Shuangjiangkou dam with a vertical core. Located on the upper reach of the Dadu River in Sichuan, China, the dam is 314 high, one of the highest dams in the world. The overburden at the dam site is relatively shallow (48–57 m) and was excavated so that the vertical core could be constructed on the bedrock.
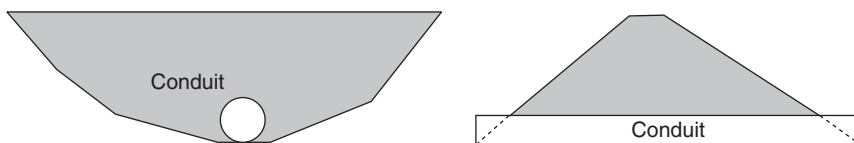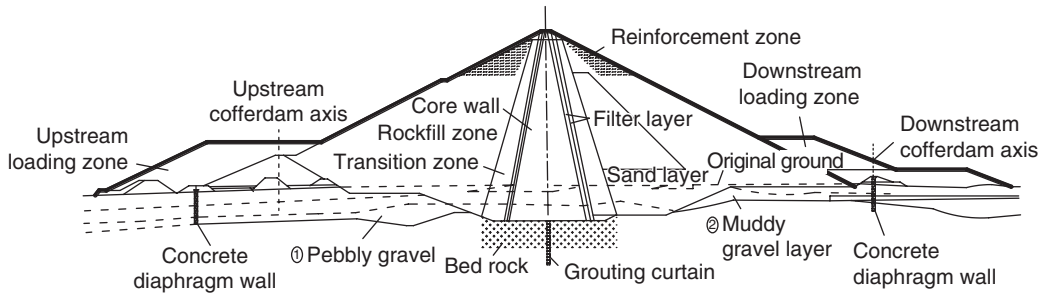

Figure 1.1   A homogeneous dam with a conduit

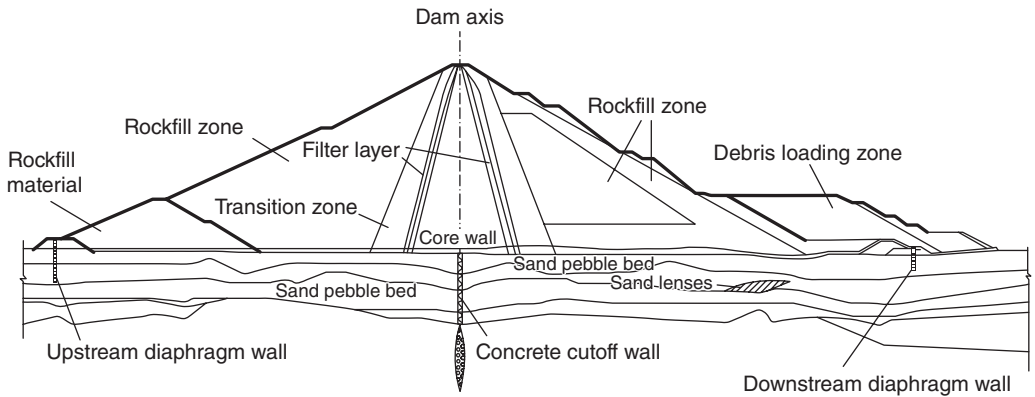**Figure 1.2** A section of the 314 m high Shuangjiangkou rockfill dam

Figure 1.3 A section of the Pubugou rockfill dam with a vertical earth core

When the overburden is thick and pervious, cut-off walls may be required to minimize the seepage through the foundation and seepage-related problems in the foundation and the abutments. The cut-off walls for the 186 m high Pubugou rockfill dam are shown in Figure 1.3 as an example. This dam is also situated on the Dadu River in Sichuan, China. The maximum overburden thickness is 78 m. The overburden alluvium materials are gap-graded, and highly heterogeneous spatially. Hence two concrete cut-off walls were constructed through the over-burden. The connection between the core and the walls was carefully designed to avoid stress concentrations and to alleviate the unfavorable influence of the large differential settlement between the walls and the surrounding soil. A highly plastic clay zone was constructed; one cut-off wall was embedded in the plastic clay and the other wall was connected to a drainage gallery, which was in turn embedded in the plastic clay.

A sloping upstream earth core may be adopted (Figure 1.4) when weather conditions do not allow the construction of a central vertical core all year round. The sloping core and the filters can be placed after the construction of the downstream rockfill. In this way, during staged construction, the rockfill can be placed all year round while the sloping core is placed during the dry season when mixing of the clayey core materials is practical. Figure 1.4 shows a section of the 160 m high Xiaolangdi dam with a sloping core. The bottom width of the core is 102 m and the core is extended to the upstream cofferdam through an impervious blanket. The overburden exceeds 70 m and two concrete cut-off walls were constructed, one beneath the sloping core and the other beneath the upstream cofferdam.
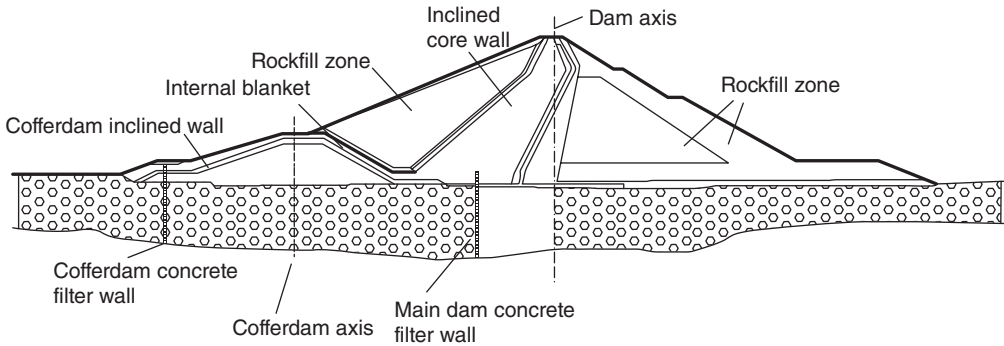
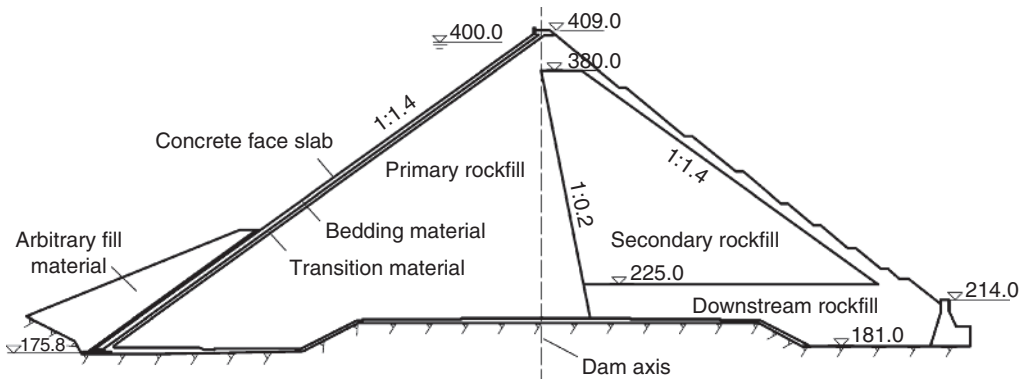**Figure 1.4** A section of the Xiaolangdi dam with an inclined earth core

Figure 1.5 A section of Shuibuya concrete-faced rockfill dam

The seepage through a rockfill dam can also be controlled by placing an impervious reinforced concrete plate at the upstream face of the dam. Such a dam is termed as a concrete-faced rockfill dam (CFRD). Figure 1.5 shows a section of the 233 m high Shuibuya CFRD located on the Qingjiang River in Hubei, China. A CRFD consists of the rockfill, the face plate, and transition and filter zones. The rockfill provides free drainage and high shear strength so that the profile of the dam can be smaller than that of a cored dam. The reinforced concrete face plate is cast with longitudinal and transverse joints and waterstops to allow for differential movements of the plate. The transition zone serves as a cushion to support the face plate. When the joints leak or the plate cracks, the transition and filter zones also limit the leakage, and the filter between the transition zone and the rockfill prevents internal erosion at the interface. CFRDs have been the most common type of high rise rockfill dams over the past decade. Since 1985, more than 80 CFRDs higher than 100 m have been constructed or are under construction in China (Jia et al., 2014). However, separation of the face plate from the cushion and extruding rupture of the face plate have occurred in several CFRDs.
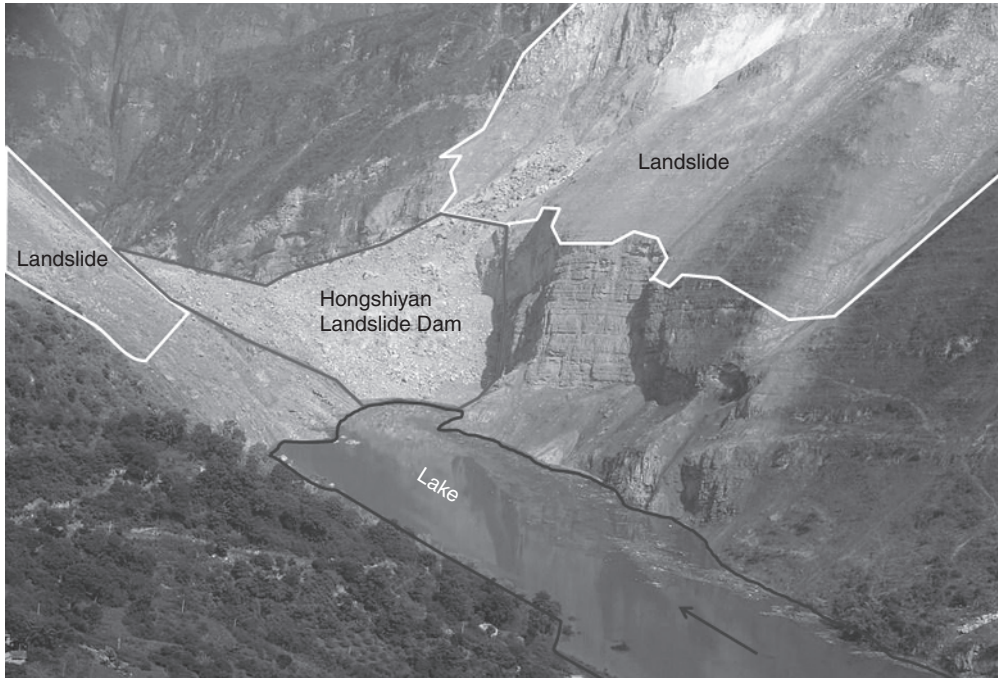
Figure 1.6   The Hongshiyan landslide dam formed on 3 August 2014 in Yunnan Province, China

1.3   Landslide Dams

A landslide dam is part of a natural landslide deposit that blocks a river and causes damming of the river. Once the river is blocked, the lake water level may rise quickly in the flood season since there is no flood control facility for such a natural dam. The dam may therefore be overtopped within a short period after the formation of the dam. For this reason, the risks posed by a landslide dam are rather high.

Figure 1.6 shows a recent landslide dam, at Hongshiyan, which was triggered by an earthquake on 3 August 2014 in north-eastern Yunnan Province, China. Landslides occurred on both sides of the Niulan River at Hongshiyan and formed a large landslide dam with a height of 83 m, a width of 750 m and a dam volume of $12 \times 10^6 \, \mathrm{m}^3$. The large lake with a capacity of $260 \times 10^6 \, \mathrm{m}^3$ threatened more than 30,000 people both upstream and downstream of the landslide dam.

1.4   Concrete Gravity Dams

A gravity dam is an essentially solid concrete structure that resists imposed forces principally by its own weight (Jansen, 1988) against sliding and overturning. Gravity dams are often straight in plan although they may sometimes be curved to accommodate site conditions. Along the dam axis, the dam can be divided into an overflow section and a non-overflow section. The dam is constructed in blocks separated by monolith joints (i.e. transverse contraction joints) and waterstops. The monolith joints are vertical and normal to the dam axis, cutting through the entire dam section. Therefore, when analyzing the safety of a concrete gravity dam, one or several blocks may be assumed to fail simultaneously. Since the stability is of primary concern in designing a gravity
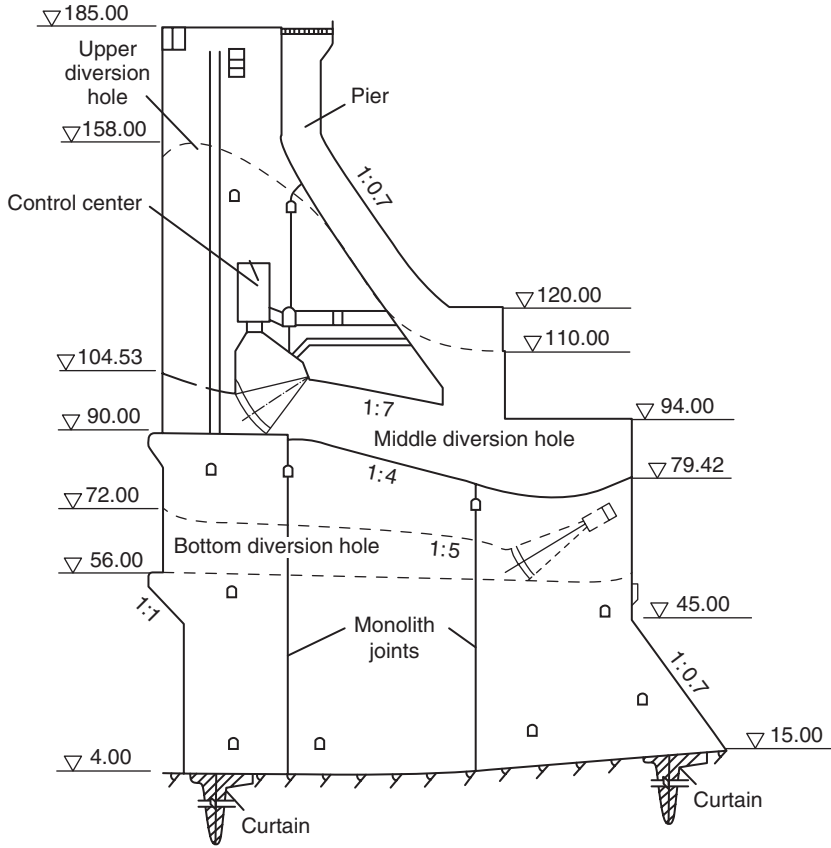
Figure 1.7　An overflow section of the Three-Gorges concrete gravity dam

dam, the treatment of its foundation is of paramount importance. In addition, grouted curtains are preferred to cut off the underseepage and minimize the uplift force on the base of the dam.

Figure 1.7 shows an overflow section of the 181 m high Three-Gorges concrete gravity dam. The dam has an axial length of 2309.47 m and a crest width of 15 m. Two curtain walls were grouted in the foundation, one near the upstream and the other near the downstream of the dam.

1.5　Concrete Arch Dams

A concrete arch dam is a shell structure that is curved both longitudinally and transversely. The water pressure is transferred to the abutments through the arch effects, and the primary load in the arch dam is compressive. Since concrete has high compressive strength, the cross-section of an arch dam can be significantly smaller than that of a concrete gravity dam. Due to the very large thrust loads, the stability of the abutments is critical to the success of an arch dam.

Figure 1.8 shows the construction of the 305 m high Jinping I arch dam in China. The widths of the crest and the base of the arch are 13 m and 58 m, respectively. Fractured rocks and deep tension cracks were found on the left abutment. Hence a deep key was excavated into the left abutment and a 155 m tall concrete foundation was constructed to ensure the safety of the abutment.
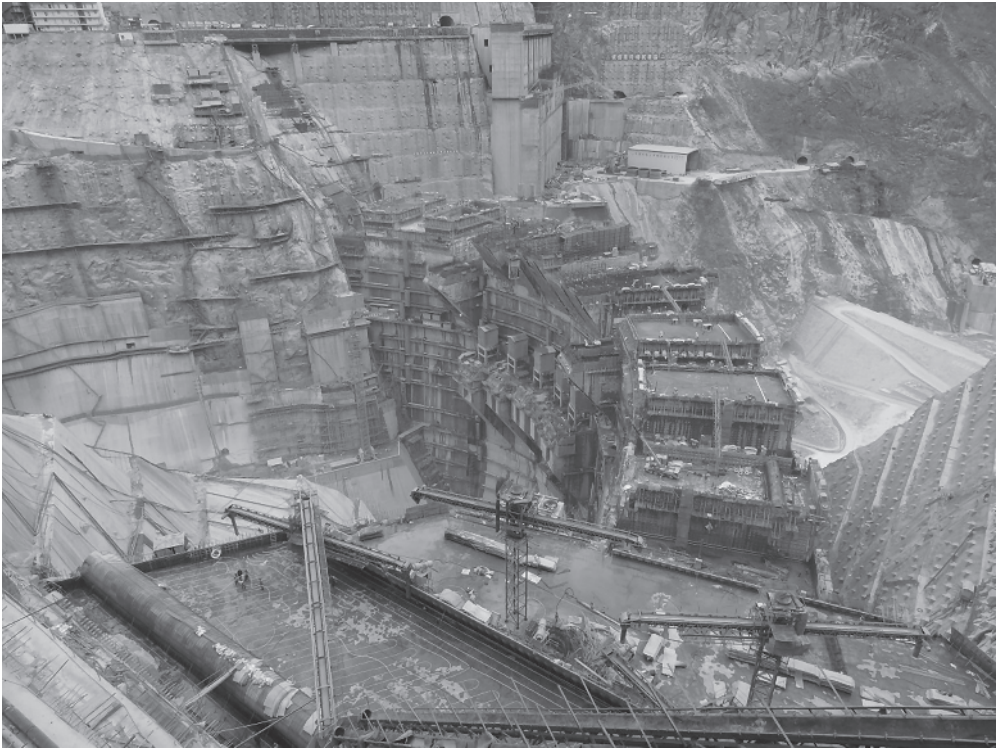
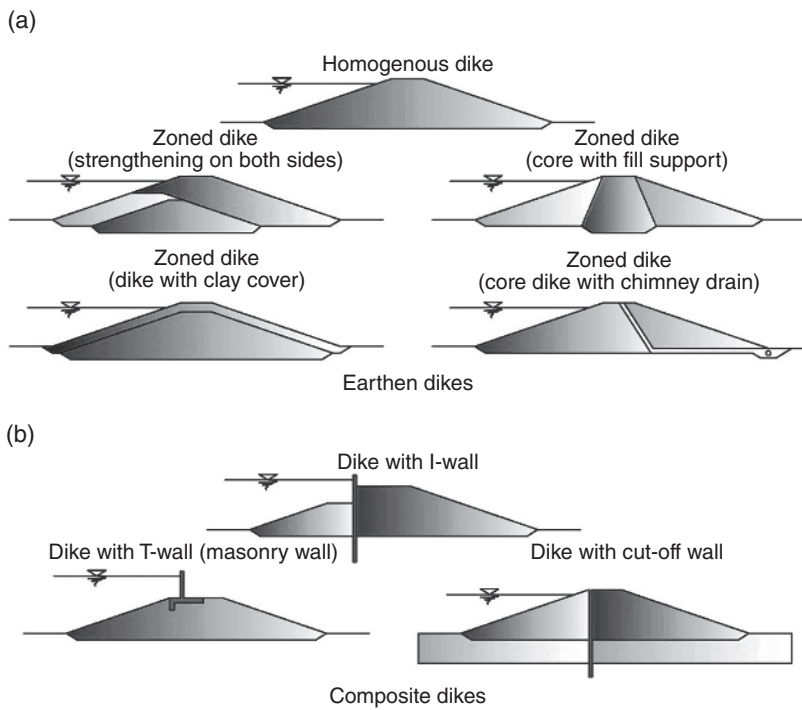**Figure 1.8** The Jinping I arch dam and its left abutment foundation

(a)

Homogenous dike

Zoned dike
(strengthening on both sides)

Zoned dike
(core with fill support)

Zoned dike
(dike with clay cover)

Zoned dike
(core dike with chimney drain)

Earthen dikes

(b)

Dike with I-wall

Dike with T-wall (masonry wall)

Dike with cut-off wall

Composite dikes

Figure 1.9 Classification of dikes. *Source:* Danka (2015). With permission from ASCE

1.6 Dikes

Two main categories of dikes – earthen dikes and composite dikes – are differentiated as shown in Figure 1.9. The earthen dikes are constructed only of granular or cohesive soils, with the materials satisfying requirements of water retention and stability. There are two different types of earthen dikes: homogeneous and zoned dikes. Homogeneous dikes are built in places rich in fine-grained soils, which is favorable as it has low permeability and high resistance to erosion. Zoned dikes are preferred when there is a lack of good quality fine-grained soils. This type of structure is popular, since the application of coarse fills can lead to savings on the use of fines. Two main types of zoned dikes are common: those with an impermeable core supported by fills, and those with an impermeable mask on the top of a fill material. In Figure 1.9, only one configuration of impermeable core is illustrated, but other layouts are also used. A special type of earthen dike is formed due to historical strengthening. This multi-layer structure is formed piecemeal as the safety standards evolve or as social needs lead to the heightening of a former section. The characterization of such dikes is challenging due to the lack of accurate information about historic geometries, and differences in construction and quality management methods.

Composite dikes include additional superstructures or embedded structures such as T-wall, I-wall, masonry wall, cut-off wall, gateway, spillway, and discharge pipes. The common layouts are presented in Figure 1.9b. T-walls or I-walls can increase the elevation of the crest hence lower the probability of overtopping. The use of such walls can also lead to a smaller dike width compared with earthen dikes of the same elevation, thus saving space. Application of retaining structures on the water side can also serve the purpose of enhancing surface protection against erosion. Cut-off walls are used to prevent seepage through the subsoil or the embankment.