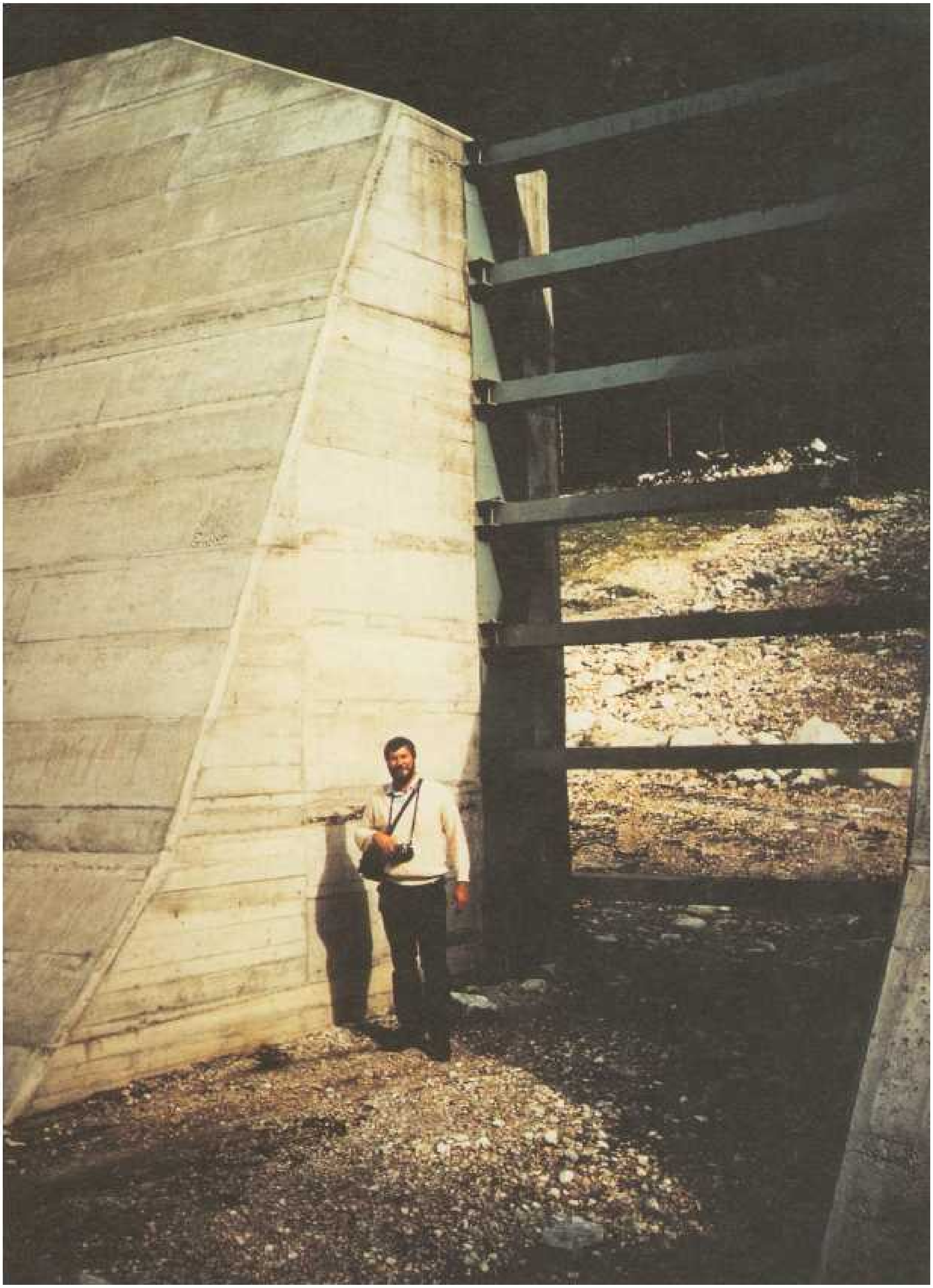

FIGURE 4.13 Screen attached to a check dam. Location: Canton of Zurich, Switzerland. *Photo: F. Zollinger.*

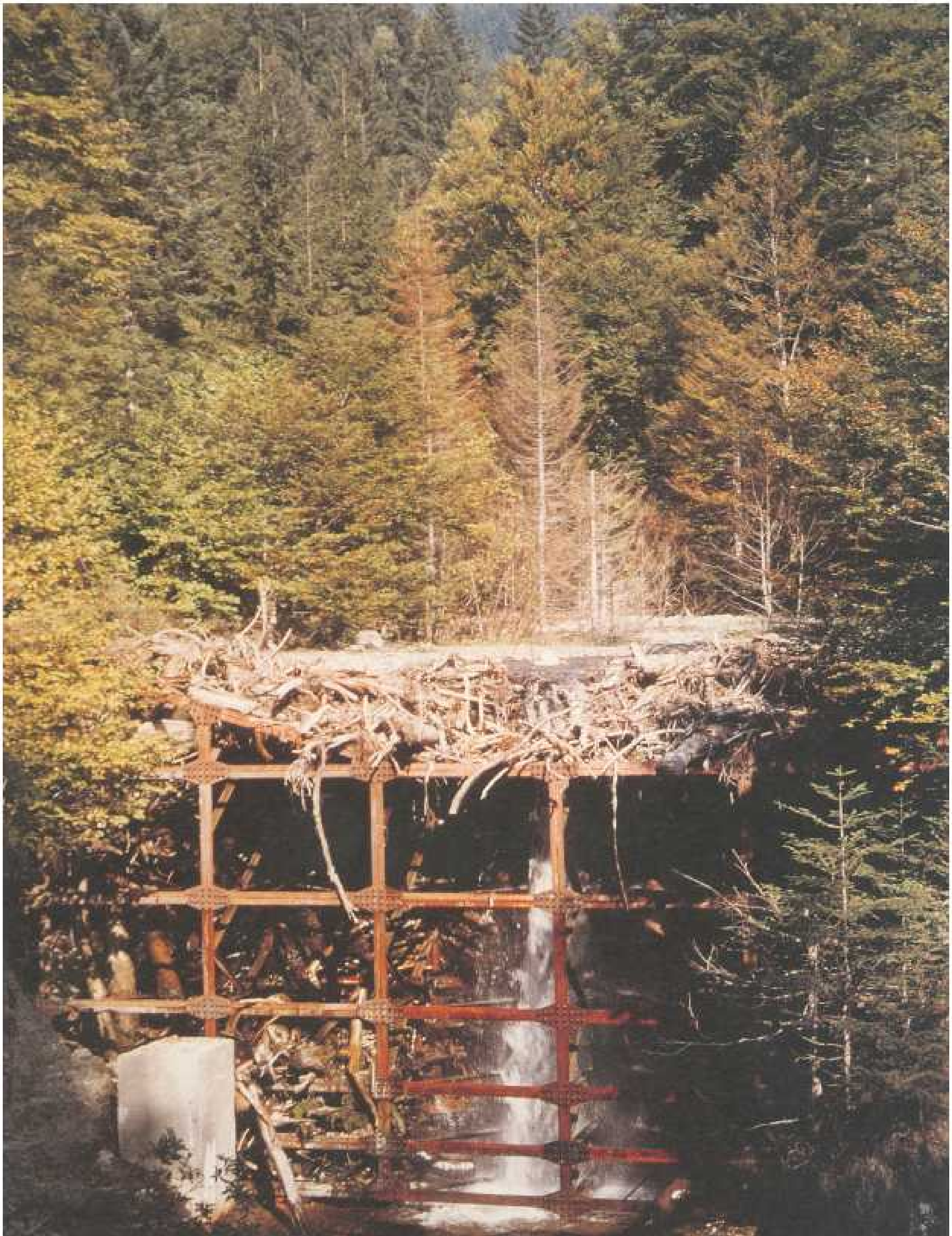

FIGURE 4.14 Steel-lattice dam in Kirchbachgraben, Austria. *Photo: G. Kronfellner-Kraus.*

FIGURE 4.15 Flyover composed of guidewalls and a smooth channel. Location: Canton of Bern, Switzerland. *Photo: M. Watanabe.*

(b2) *Removal of drifting debris*

Drifting debris such as wood and timber often plug a gorge or channel at a bend, bottle-neck or bridge, thus forming a natural dam, whereupon overflowing takes place. Such a natural dam is unstable; sooner or later it is breached, causing another surge in the mudflow. Particularly on a fan, a plug created by drifting debris can cause unexpected flooding.

A screen attached to an ordinary check dam (*Fig. 4.13*) and a steel-lattice dam (*Fig. 4.14*) have proved to be effective in removing drifting debris. A wide area with a gentle gradient such as the reservoir of a check dam or a sand pocket is also effective in arresting drifting debris.

(b3) *Reduction of discharge volume and peak discharge*

The magnitude and extent of damage and loss due to a mudflow are proportional to the volume discharged, as noted in Chapter 1. The reduction of the volume of material in a mudflow can be achieved by creating check dams and sand pockets. The required number of such structures and their total capacity should be estimated on the basis of the anticipated volumes and frequency of mudflows.

(b4) *Hazardless passage*

Provided that its volume is limited, appropriate civil engineering works can channel a mudflow, control its path and ensure its orderly descent. A flyover, as shown in *Figure 4.15*, can allow a mudflow to pass safely over roads, railways and other structures, and thus protect them. This method is widely employed in mountainous regions in Austria, China, Japan and Switzerland.

In case of a shortage of funds or lack of proper sites for engineering structures, diversion is recommended if the topography permits it. Lateral diversion can be conveniently achieved by means of a guiding wall or deflection dam. For example, Britar City at the foot of Mt. Kelut in Indonesia has been protected in this way (*Fig. 4.16*).

An artificial hillock of sufficient height, built in close proximity to a village or to an individual dwelling lying in the anticipated path of a mudflow, can serve as a refuge for those who can reach it in time in the event of a mudflow (*Fig. 4.2*). At other times, it can serve as a recreation area for the local community.

FIGURE 4.16 Diversion dam at Britar City. The dam blocks the channel towards Britar City. Location: East Java, Indonesia. *Photo: M. Watanabe.*

4.2.2. Design aspects of various structural measures

The types, dimensions, locations, number and sequence of construction of preventive structural works should be determined not only from design manuals, but also by field observations, monitoring, experience in mudflow disasters and experimental studies. Preventive structures employed improperly may result in additional damage, especially because they generate a false confidence among the general public that they are protected against mudflows.

The structural design of most preventive works is not particularly difficult. It is essential to select appropriate sites, determine the proper dimensions and ensure the integrity of the structures. An outline of major types of preventive structural works, together with some design aspects and technical points, are presented in the following subsections.

4.2.2.1. *Hillside works*

Denuded slopes are much more vulnerable to erosion and landslides during heavy rainfall than slopes with vegetation cover. Such slopes may result from deforestation or volcanic eruption.

To replenish vegetation cover on a slope, the first step is to seed it with grasses. It is advisable to plant indigenous species of grass as "pioneer vegetation". After it has taken root, appropriate species of bushes and trees can be introduced.

Simple structures should be employed for conserving top soil and to channel runoff so as to foster the growth of stabilizing vegetation. An example of hillside works consisting of terracing for afforestation is illustrated in *Figure 4.3*.

4.2.2.2. *Check dams (Sabo dams)*

A check dam, or Sabo dam, is one usually built perpendicular to the direction of the flow in a channel bed to stop debris. The vacant space or reservoir created by a check dam is effective in arresting debris, especially the coarse material carried by a mudflow. It is designed to resist the impact caused by a mudflow and the pressure exerted by mud and debris deposited behind it, by virtue of its own weight. A check dam is also effective in con-

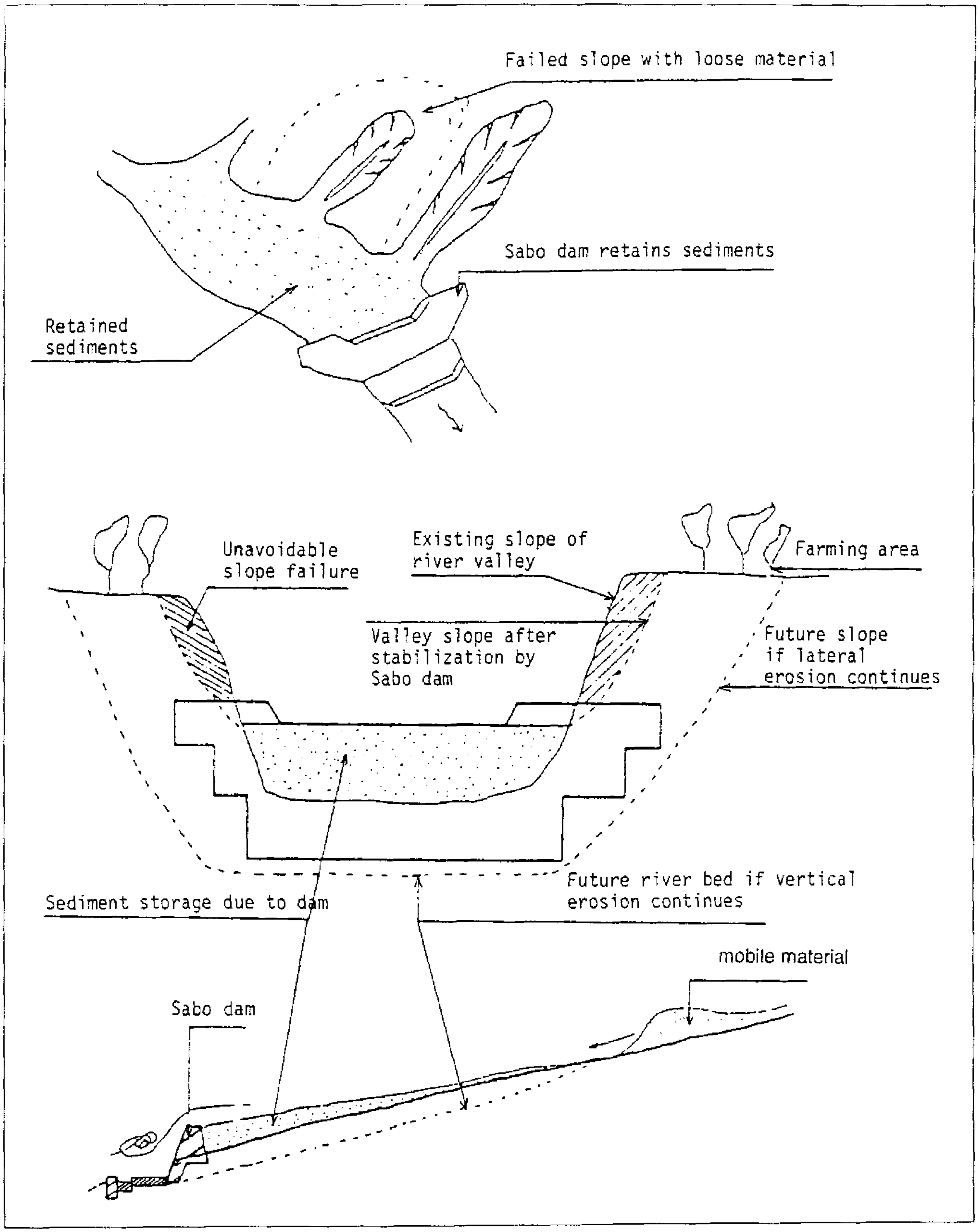

FIGURE 4.17 Typical configuration of a concrete check dam in sediment-control work (Supangkat, 1989).

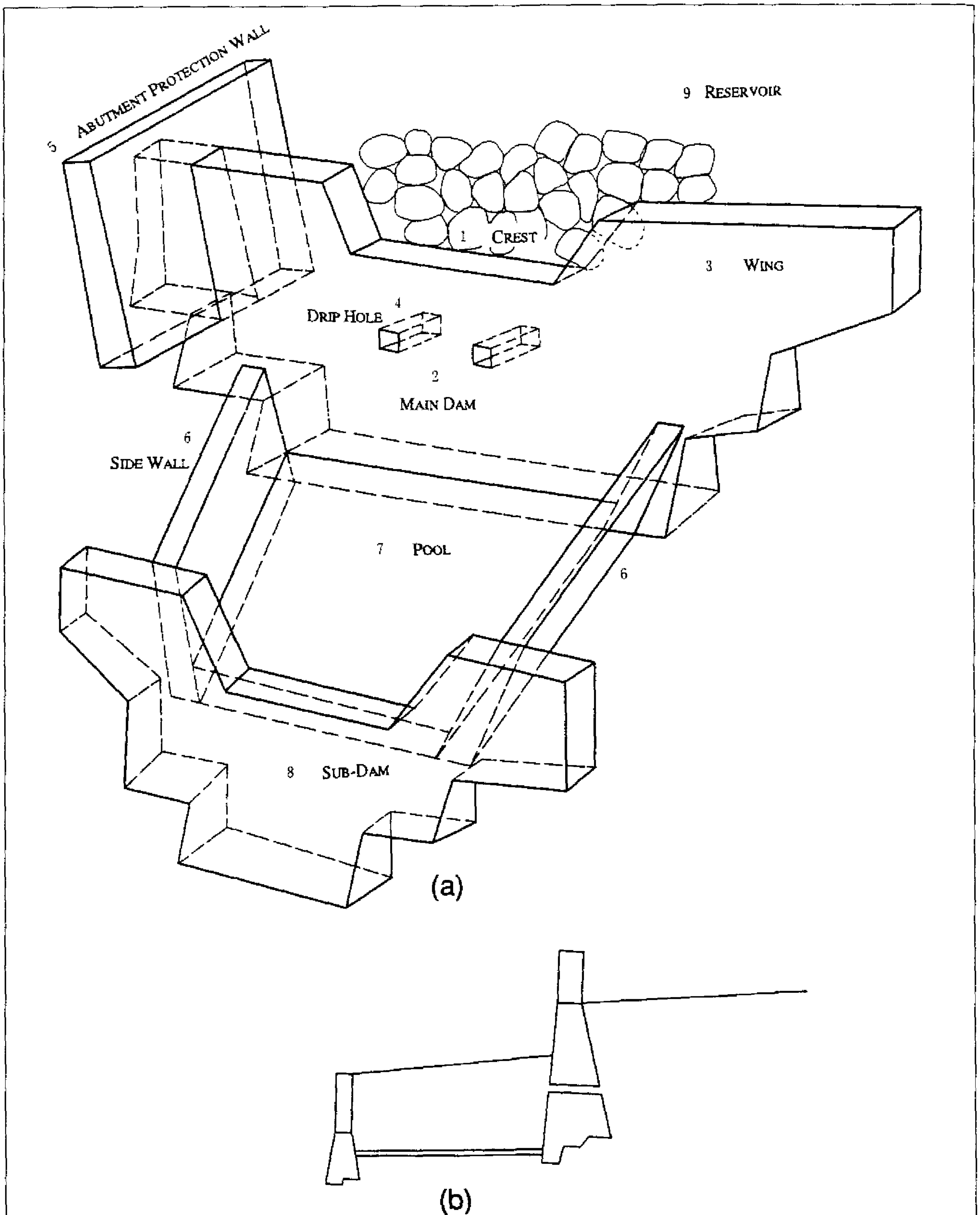

Figure 4.18 Components of a check dam: (*a*) Three-dimensional view; and (*b*) Longitudinal section.

solidating and sorting debris material Furthermore, it prevents the degradation of a valley floor and lateral erosion. Some typical check dams are shown in *Figures 4.7, 4.10, 4 11* and *4.12*.

A check dam is constructed at a valley mouth or where a bottle-neck site is available. The closer a check dam is to the source of the material, the more effective it is (functions of a check dam are illustrated in *Figure 4.17*). This is why check dams are constructed in remote catchment areas (as in *Fig 4 7*). However, it requires a very large expenditure and a long period of time to construct check dams in such a catchment. A series of check dams is built if the gradient is steep and if a large mudflow discharge is expected.

In most cases, check dams are made of wet masonry or concrete to ensure their stability and strength. Reinforced concrete can be replaced by wood, rocks and boulders, to some extent, if available at the site. An economic alternative is to use rock-filled gabions with concrete covers. For a given check dam, the material should be selected taking into account the estimated force of impact of the boulder-studded front of a mudflow and the energy of the running water. Naturally, the more solid the construction, the longer the dam may be expected to serve.

The effectiveness of a check dam in reducing the risk of mudflows is proportional to its storage capacity. This capacity increases with an increase of the height of the dam. On the other hand, the kinetic energy of a flow, and hence the hazard to the stability of a dam and its foundation, increase in proportion to the square of the height of the dam.

The design of a check dam depends on the following conditions:

(*a*) Topography of the dam site (e.g., bed slope, river width, height of abutment);

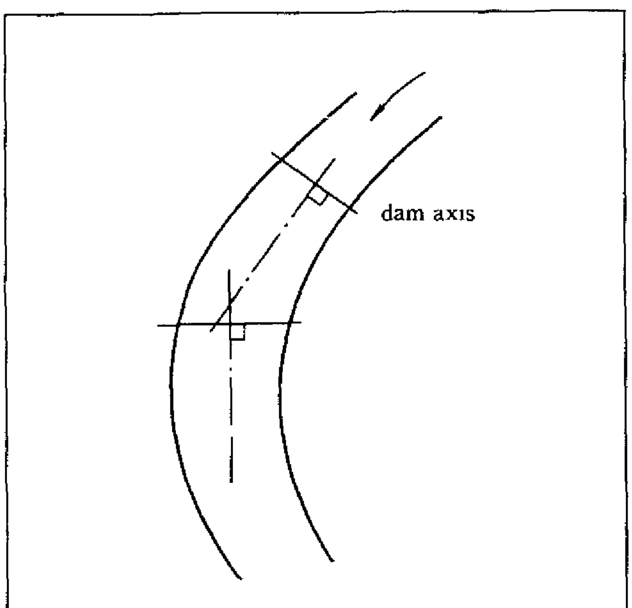

FIGURE 4 19 Relationship between flow direction and check dam axis. The dam should be perpendicular to the alignment of the downstream channel.

(*b*) Geology of the dam site (e.g., type of soil or rock in foundation and abutment),

(*c*) Storage capacity required; and

(*d*) Building materials available for construction of the dam.

The essential elements in designing a check dam (*Fig. 4.18*) are as follows:

(*a*) Direction of dam axis: The dam axis must be perpendicular to the downstream channel (*Fig. 4.19*);

(*b*) Dimensions of dam elements:

(i) *Crest*: As a rule of thumb, the width of the crest must be greater than 2 m, otherwise it may not be sufficiently resistant to the flow energy;

(ii) *Downstream slope*: The gradient of the downstream slope must be about 1:0.2;

(iii) *Upstream slope*: The gradient of the upstream slope must be determined on the basis of two-dimensional stability analysis;

(iv) *Conduit*: The area of the conduit must be large enough to accommodate the peak discharge of the potential mudflows;

(v) *Wing*: The wing must be sufficiently anchored at the abutment, which must be well-compacted and covered with revetment work. If the check dam is in a bend, the wing should have a height exceeding the superelevation at the outside of the bend, so that there is no overflow and erosion of the abutment. In such a vulnerable location, the wing should penetrate at least 2 m into the abutment;

(vi) *Foundation*: The foundation of a dam must be resistant to sliding and, most important, to local scouring, which is the major cause of dam failure. For this purpose, the foundation must be at least 2 m deep, and the opening must be refilled tightly if the foundation is composed of mobile sand and stones;

(*c*) Mudflow discharge capacity:

(i) The design mudflow peak discharge must be estimated on the basis of past records, making maximum use of flood marks left by the peak discharge and by superelevation;

(ii) In the case of an extreme mudflow event, the sediment transport may be as high as the flood discharge. The extreme sediment yields from a drainage basin can also be estimated by the Kronfellner-Kraus formula (see Section 3.3.1);

(*d*) Stability analysis: Static analysis should be performed to ensure the stability of a dam.

Appurtenances:

1. It is recommended that a pool be made in order to dissipate the kinetic energy of a flow. A ground sill or a sub-dam constructed as far downstream as 1.5 or 2 times the height of a dam, is effective in forming a pool and is thus beneficial in preventing local scouring (see *Fig. 4.18*). As mentioned previously, local scouring is the major cause of dam failure.

2. Side walls between the main dam and the sub-dam, if they are to be constructed, must be sited clear of falling objects from the crest so as to avoid direct hits.

3. The crest of the sub-dam must be at a higher level than the foundation of the main dam, in order to ensure a sufficient depth of the pool between them. The depth of the pool, which depends on the height of the check dam, must be more than 2 m.

4.2.2.3. *Sand pockets*

The key function of a sand pocket is to accommodate almost all the debris in a mudflow and to alter the flow mode to a flow with normal suspended sediment load. It consists of an embankment surrounding an area designated for mudflow deposition (*Fig. 4.20*). Thus, the harmful spread of mudflow is localized to the area, and does not reach inhabited and agricultural lands.

The hazard map in *Figure 5.3* (Chapter 5) shows the location of sand pockets on Mt. Kelut in Indonesia and *Figure 8.11* (Chapter 8) shows a photograph of one of those sand pockets, on the Konto river.

A sand pocket is normally situated in an area where an alluvial fan is formed. The inlet of a sand pocket must be fixed at the upper reach of the intersection point, otherwise a flow may take a course behind the embankment of a sand pocket.

The required number and capacity of sand pockets depend on the anticipated frequency and volume of future mudflows, and on the topography of the area. The storage capacity of a sand pocket depends on the height of the embankment which surrounds it. However, the height of the embankment may need to be limited if the quality of the construction material available at the site is poor or if the foundation is unreliable. Sandy materials, although they can be compacted, are not resistant to seepage. A sand pocket must be laterally shifted or expanded as soon as it is filled, in order to make allowance for further capacity.

4.2.2.4. Channel works

A natural channel on an alluvial fan frequently, and sometimes abruptly, alters its course. Its longitudinal profile and cross-section are also continually changing due to aggradation in some reaches and degradation in others, caused by siltation and erosion, respectively. In general, the higher the sediment load, the more unstable the channel. The instabilities of a channel result in problems such as local scouring, overflowing and bank breaks.

The objective of channel works is to keep hazardous changes in the following elements of a channel within acceptable limits:

(a) *Bedslope*: When the bedslope is suddenly reduced, sedimentation takes place. This can lead to bank breaks and overflows. On the other hand, if the bedslope increases because a flow gains momentum, scouring occurs. Therefore, the bedslope must be maintained in such a way as to ensure equilibrium in the channel, preventing both sedimentation and erosion

(b) *Alignment*: The alignment of a channel on a fan must be as straight as possible in order to avoid bending, which could result in local bar formation, scouring of the undercut-slope and overflowing due to superelevation.

(c) *Level of channel bed*: The level of the channel bed rises with continuous siltation. However, it must be kept lower than that of the surrounding land, even though this is a difficult and time-consuming process.

(d) *Cross-sectional area*: The cross-sectional area of a channel must be large enough to accommodate the peak discharge. If the cross-sectional area of a channel becomes smaller due to sedimentation, the discharge capacity is reduced and overflows may occur.

Properly-built channel works ensure that the design discharge (estimated on the basis of historical data or flood marks left by past events) can safely pass along the channel.

Various training (control) measures described below can be helpful in avoiding hazardous changes and ensuring smooth flow.

(*a*) Measures for erosion control, streamline regulation and bedslope reduction:

(i) *Filling works*: Spots vulnerable to erosion can be protected by using, for example:

- **Large-sized material (gravel, stones, concrete blocks);**
- **Sand bags, if large-sized material is not available;**
- **Gabions made of bamboo, filled with stones and/or gravel (*Fig. 4.21*);**
- **Gabions made of iron wire.**

(ii) *Revetment works*: These consist of facings on soil or soft rock embankments to prevent scouring. They may be made of masonry or concrete.

(iii) *Ground sills*: These are low dams or barriers in a small stream, whose purpose is to retard bottom erosion. They can be built of wood, gabions, masonry or concrete (see *Figs. 4.4, 4.5* and *4.6*).

(*b*) Measures to cope with sedimentation, such as dredging.

(*c*) Measures to cope with shifting trouble spots:
Trouble spots caused by local scouring and sedimentation usually shift, in such a way that the remedial structures which have been put in place are sometimes damaged, and new trouble spots develop. This shifting is caused by the formation of sand bars on the channel bed. Ground sills set up in series (see *Figs. 4.4, 4.5* and *4.6*) have proved to be effective in preventing the development of sand bars.

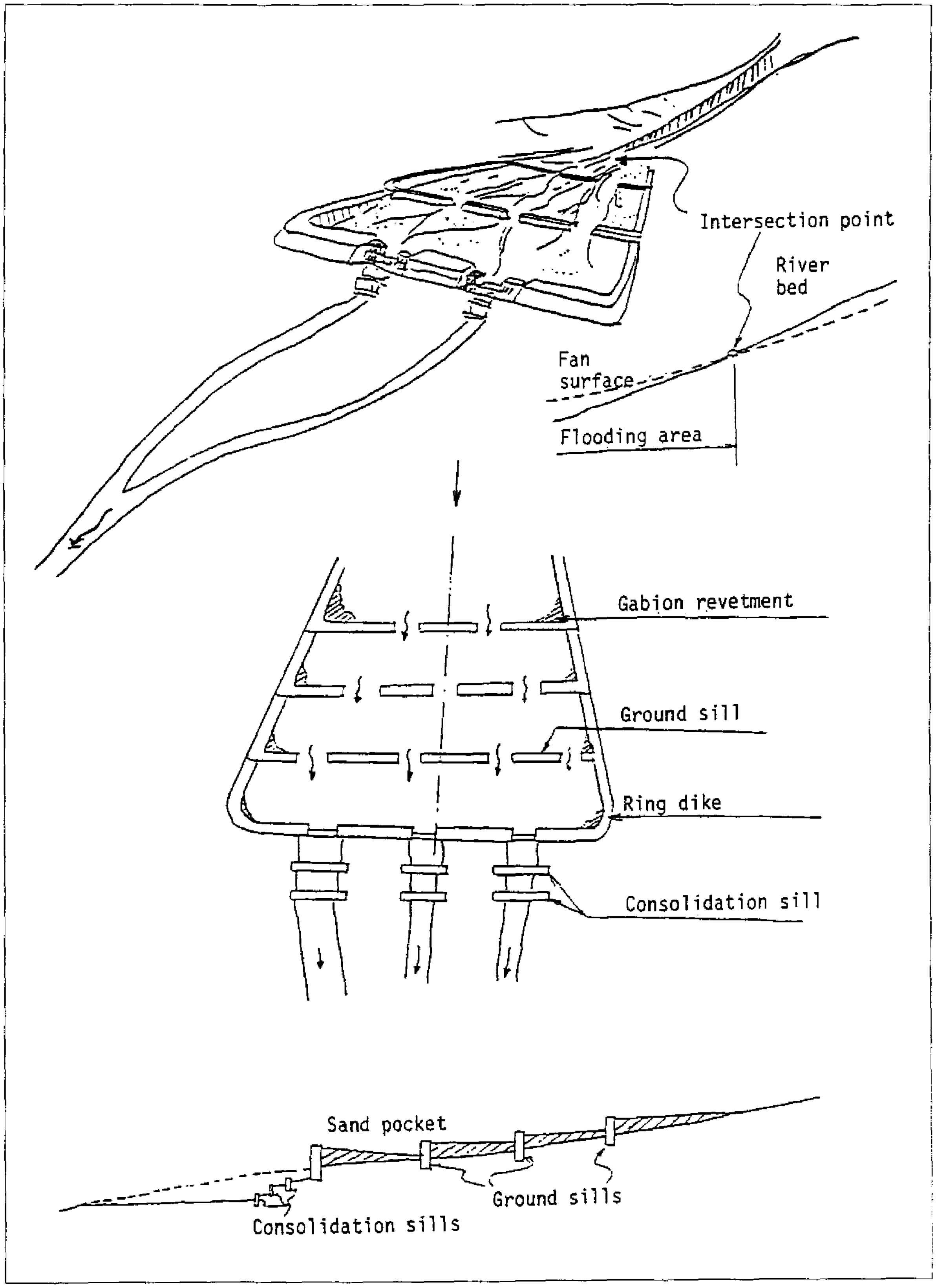

FIGURE 4.20 Formation of sand pockets.

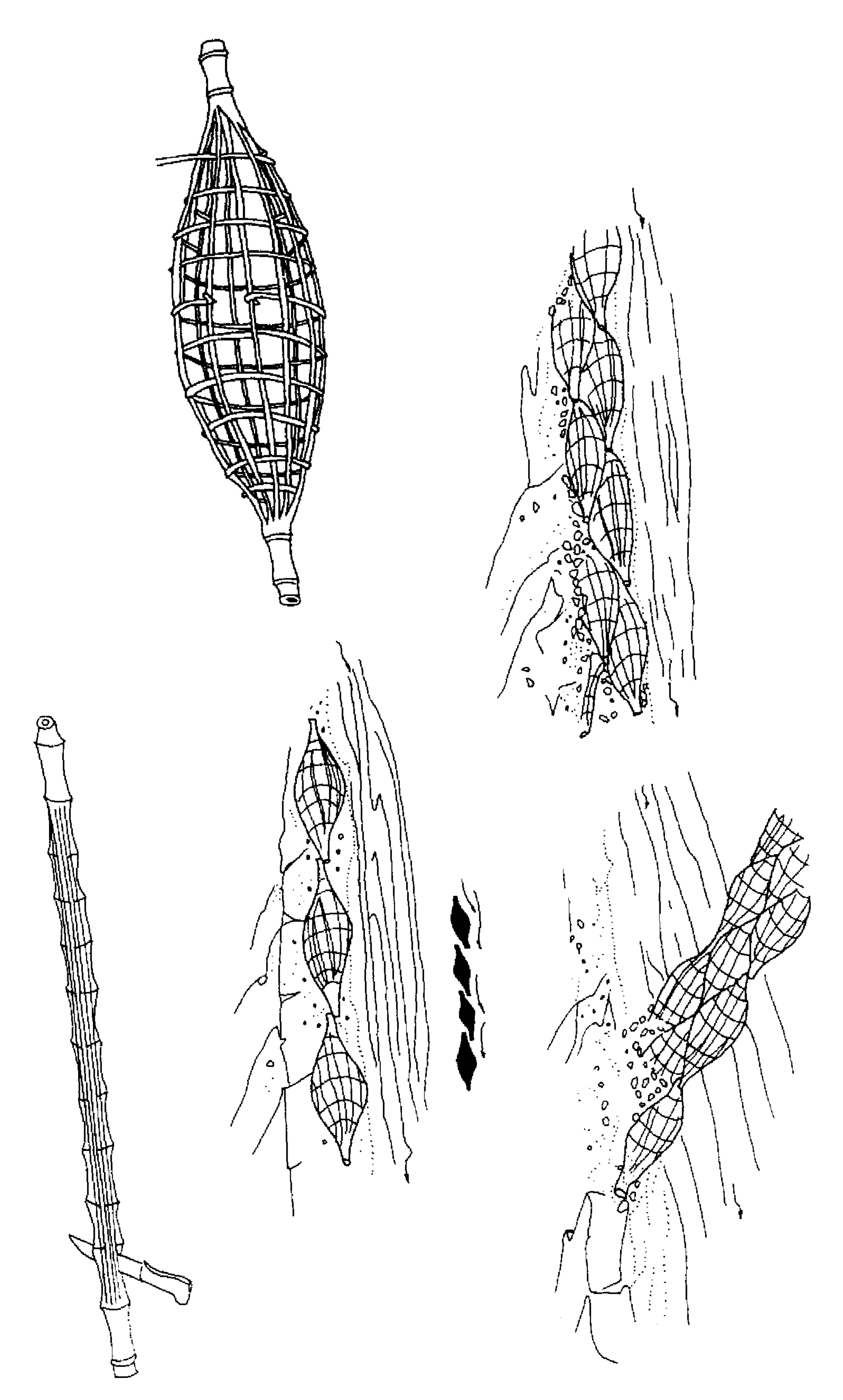

FIGURE 4.21 Various possibilities for making gabions out of bamboo, and their use.

4.2.2.5 *Protective works for earthfill dams and tips*

The failure of an earthfill dam caused by overflowing flood water or an earthquake, for example, can produce a mudflow disaster. Such failures are more common in the case of tips or dams, which store the spoil of mining operations, material excavated from a construction site or industrial waste. Although they are structurally similar to earthfill dams, they are usually constructed with little or no attention to engineering aspects. Hence, the possibility of their failure is generally much higher than in the case of well-designed earthfill dams.

An earthfill dam may fail because of sliding, liquefaction, scouring and undermining, or piping. Various measures to strengthen and protect an earthfill dam or a tip are described below:

(a) *Good compaction*

Tight contact between the grains resulting from good compaction by a heavy bulldozer or a vibrator provides high resistance to sliding, because the particles are locked by the adjacent ones and cannot move easily. Moreover, when the particles of a cohesionless material (e.g., sand) have a loose structure (*Fig. 4.22*) and the voids are filled with water, most of the weight is supported by water. When vibration occurs, during an earthquake, for example, the unstable structure tends to collapse. This causes a sudden increase of the pore water pressure when the water filling the voids cannot quickly drain. If the pore water pressure becomes equal to the overburden pressure, there is a complete loss of contact stresses between the grains. As a result, the material in the dam loses its shearing resistance and flows like a liquid, a phenomenon known as *liquefaction.* Fine uniform sands with a mean diameter of approximately 0.08 mm to 0.2 mm are most susceptible to liquefaction. Well-graded soils with coarse particles are unlikely to liquefy. In poorly compacted earth materials, uncontrolled seepage and high seepage gradients may cause piping and internal erosion, which may lead to the failure of the dam.

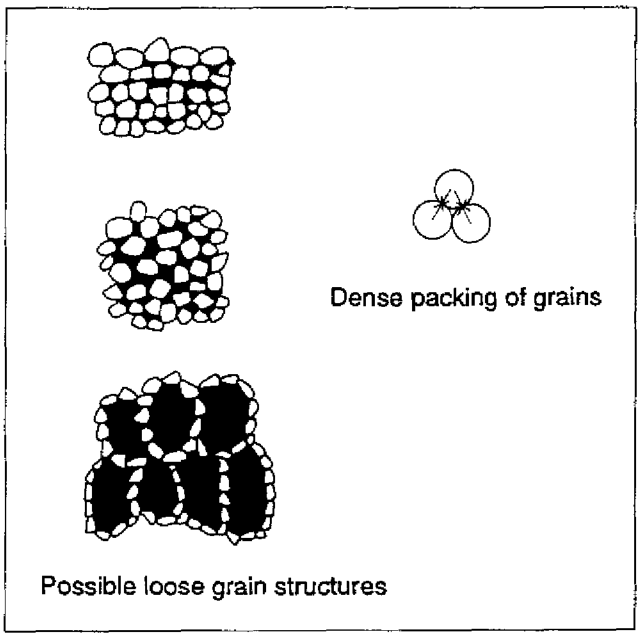

FIGURE 4.22 Structure and packing of material grains.

(b) *Strong foundation*

An earthfill dam or a tip should also be built on a strong foundation, in which there is no possibility of failure by sliding or by liquefaction.

(c) *Well-designed cross-section*

The cross-section of an earthfill dam should be properly designed to guarantee its stability against shear and piping failure. This can be achieved by zoning; i.e., by providing a number of zones with different materials having different properties. Such zones usually include an impervious core, filter zones as a defence against piping, and drainage zones which collect water seeping through core and filter zones, thus preventing internal erosion.

(d) *Provision of spillway with sufficient capacity*

A spillway must be provided having a crest whose elevation is below that of the dam, in order to allow the discharge of excess water. Its discharge capacity must be large enough to accommodate the probable maximum flood and to prevent overtopping of the unprotected earthfill dam.

FIGURE 4.23 Poor design and construction always result in reduced efficiency and endanger the structure. Photograph shows ground sill endangered as a result of degradation and scouring. Location: Valais, Switzerland. *Photo: M. Watanabe.*

FIGURE 4.24 Check dam in which the foundation as a result of scouring disintegrated completely. Location: Yogyakarta, Indonesia. *Photo: M. Watanabe.*

FIGURE 4.25 Outlet of a sand pocket where the toe of the retaining structure was scoured. It is essential to construct a pool at the toe of the dam in order to avoid local scouring caused by flood water. Location: East Java, Indonesia. *Photo: M. Watanabe.*

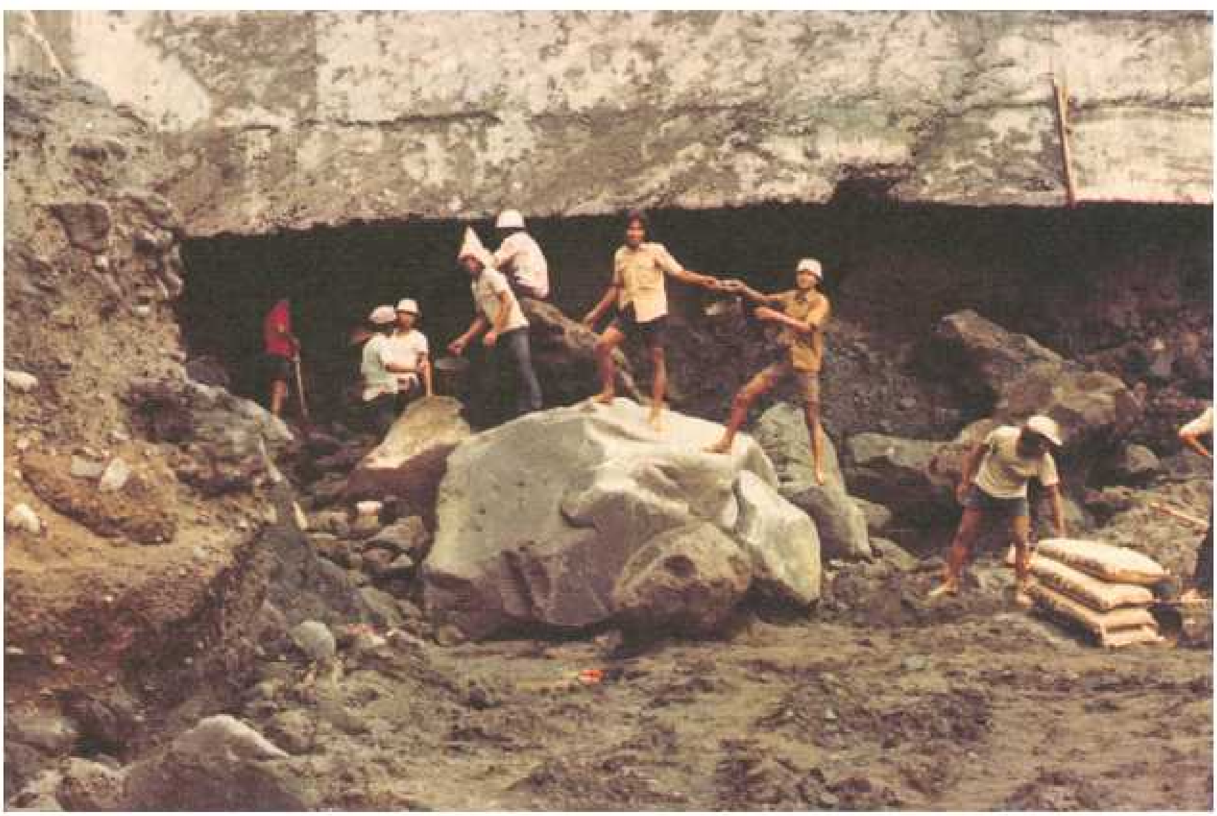

FIGURE 4.26 Destruction caused by scouring of the foundation of a check dam. Scour protection can be achieved by constructing a ground sill immediately downstream of the dam. Location: Yogyakarta Java, Indonesia. *Photo: M. Watanabe.*

FIGURE 4.27 Check dam destroyed because of an inadequate foundation Emergency filling work was required. Location. Central Java, Indonesia. *Photo: M. Watanabe.*

4.2.3. Monitoring and maintenance

Regular monitoring and repair are important to ensure that engineering structures can fulfil their purpose for as long a time as possible Structures built to prevent and control mudflow damage are especially subjected to destructive forces. The major causes of structural deterioration or failure are:

Erosion of the foundation, structure and/or revetment works (*Figs. 4 23 to 4.27*);

- Damage due to impact forces (e.g., boulders);
- Poor quality of construction materials;
- Inefficient quality control during construction;
- Inappropriate design.

Early maintenance can save a structure from total failure. For example, timely patching or filling at a cost of US$ 1,000 can prevent complete collapse of a structure which might cost US$ 1,000,000 to rebuild.

4.3. Non-structural measures

The structural measures described in Section 4.2 should be supplemented by various non-structural measures, in order to minimize the damage to life and property during future mudflows. The purpose of such non-structural measures is to improve hazard awareness and preparedness among local residents and administrators

Some important non-structural measures, along with references to the chapters of this monograph in which they are discussed, are

(*a*) Hazard and risk assessment and analysis (Chapter 3);

(*b*) Land-use mapping and zoning (Chapter 7);

(*c*) Mudflow disaster prevention planning (Chapter 5);

(*d*) Early warning (Chapter 6);

(*e*) Evacuation (Chapter 6),

(*f*) Disaster management (Chapter 7);

(*g*) Public information and education (Chapters 7 and 8).

Non-structural measures also include the following specific technical measures which may be very cost-effective:

- Watershed management, including the planting forests and bushes on slopes in order to stabilize the soil;
- Surface-water and ground-water monitoring and control.

Surface water should be drained, captured and safely diverted, ensuring that water content in the soil will not approach a proportion which will cause a mudflow to begin or to be triggered by a natural event such as an earthquake, avalanche, landslide, etc.

The focus in mitigating activities should be on non-structural measures Structural measures, if they are properly designed, built and maintained, may be very effective, although quite expensive. At the same time, such measures might create a false feeling of security A combination of both measures may be the most realistic and cost-effective.