9 Engineering and Technological Measures for Combating Desertification

Zhihai Gao, Chaosheng Li, Xiaohui Yang and Longjun Ci

China has accumulated rich experiences in combating desertification based on work in a number of regions and provinces. Various control measures have gradually been innovated and developed in recent decades. In addition to biological measures taken to combat desertification, mechanical approaches have been developed to stabilize shifting sands. Methods include technologies that release sand-accumulation, construction of sand barriers, chemical mulching and hydrologic solutions. Throughout China, various preventive measures have been adopted, practiced, integrated, and adapted to local conditions and suited to combat specific forms of desertification.

9.1 Mechanical stabilization and releasing accumulated sand

Initially, most efforts had been directed at blocking aeolian sand and fixing shifting sands. More recently, in addition to the long-term practice of sand dune stabilization, it was discovered that mechanical methods could artificially interrupt and control the processes of sand denudation, accumulation and movement. Release of accumulated sand is one of the mechanical measures used to control hazards caused by dune movement and sand transport. Mechanical stabilization and releasing accumulated sand are effective methods for mitigating and preventing hazards associated with sand movement.

9.1.1 Mechanical sand blocking techniques

9.1.1.1 Artificial walls (banks) to block shifting sands

Constructing sand-blocking walls (banks) is one of the simplest and oldest methods of controlling shifting sands. Walls or banks are installed downwind of mobile sand dunes and shifting sands or around settlements, mineral sites or oil fields, and along communication or transport facilities. The earliest sand-blocking walls or banks, dating back to historical times, were made of dried bricks or clay and were normally 100 cm high and 35–50 cm thick. Residual sand-blocking walls and banks can only be seen in areas with severe erosion, at the periphery of oases and in the Gobi region of northern China.

In recent decades, following long-term experiments and evaluation, methods to construct sand-blocking walls have been improved. Currently, it is more common to see sandbags used to make sand walls or banks to stop sand movements. These sandbags are made of materials durable under harsh conditions, such as hard paper covered with plastic films. This method not only reduces the high cost of material transport but is easier to install, provides quick and effective sand-blocking capabilities and is suitable for use in extremely arid areas including the Gobi desert region where materials are scarce. Sand-blocking walls or banks can be easily repaired and raised when the walls and banks are buried by shifting sands. Buried sandbags can also be reused to reconstruct new sand-blocking walls or banks after being flattened by drifting sands.

9.1.1.2 Sand sedimentation ditches

Sand sedimentation ditches are also one of the oldest methods used to block and settle shifting sand. Ditches slow wind speed and accumulate overloaded drifting sand. Based on the underlying coarse particles or adhering stratum, sand sedimentation ditches should be dug upwind of the protected target area, and the excavated soil should be used to build dykes on the outside of the sand sedimentation ditch. When the sand sedimentation ditch and dyke are overtopped by accumulated sand and are no longer effective, a new sand ditch with a dyke can be built outside of the old ditch. Alternatively, a concave profile (blow out) can be formed between the buried ditch (dyke) and the new ditch (dyke), thus extending the lifetime of the ditch.

Sand sedimentation ditches are normally used at the periphery of sandy deserts and Gobi. In these areas, there is typically a low amount of sand suspended in the air. This method is less effective in areas with a high amount of shifting sands because ditches are soon filled and quickly lose their function. The nature of the underlying soil layers should be considered while digging and constructing sand sedimentation ditches. Stones, gravel or straw should be utilized to protect dykes from wind erosion when the underlying layer is sandy. This method was used on a large-scale along the Lanzhou-Xinjiang Railway Line in the Yumen District of Gansu Province and along the Baotou-Lanzhou Railway Line in the Bohaiwan District of Inner Mongolia. Because the underlying layer is rocky and gravelly, the dykes did not need protection. In addition, the excavated rocks and gravel were used to cover nearby mobile dunes or stabilize shifting sands close to the sand sedimentation ditches.

9.1.1.3 Sand-blocking barriers

A sand-blocking barrier is also called a vertical sand barrier. The barrier changes the wind flow during turbulence and reduces wind speed upwind of the barrier. The sand-blocking barrier is made of *Phragmites australis*, *Achnatherum splendens* and *Salix sinopurpurea* or other crop residues. The upright barrier is about 1.3–1.7 m high, and its base is buried 20 cm into the ground. The base of the barrier is covered with wheat straw and stamped with sand to a height of 10 cm above the sand surface. Wooden posts or cement pillars about 1.5–1.7 m high are used as fixing posts. Depending on the strength of the materials, the pillars are installed every 2–8 m and buried to depth of 40 cm. All barriers are tightened between pillars and then attached to the pillars to ensure the stability of the barriers. The barriers are normally installed in late autumn to early winter, as the sand layer contains high moisture and it is easier to dig ditches at this time. Installation is, therefore, more cost-effective and reliable. This sand-blocking barrier is effective at stopping and accumulating shifting sands; however, this method requires a large supply of straw or other materials, which increases the cost.

Based on research and observation, the ability and effect of sand-blocking barriers to stop sand movement are significant. Barriers should be installed more than 200 m upwind and 100 m downwind of communication or transport lines, particularly in drifting sand areas of the Gobi and in flat sandland.

If the distance between the barriers is too wide, the barriers will easily erode or be destroyed, but if the distance between the barriers is too narrow, costs are too high. Therefore, a reasonable distance between barriers should be carefully calculated along with the costs of materials and manpower to ensure a cost-effective installation.

The distances between barriers erected at right angles to the main wind direction can be determined by reference to the topography and slope of the land and the proposed height of the barrier. The frequency, velocity and duration of the wind must also be considered when designing and installing the barriers. The distance between tall barriers should be wider than that of short barriers, and the distance between barriers on gentle slopes should be longer than that on steep slopes. Where wind is weak, the distance between barriers should be longer than where wind is stronger. On flat sand surfaces with less than 4° slope, the distance between barriers should average 15–20 times the height of the barrier. On windward slopes, the top of the second barrier should be parallel to the base of the first barrier.

9.1.1.4 Sand blocking networks

The theory behind sand blocking networks is similar to the sand-blocking barrier. It has been developed based on experience with sand-blocking barriers over the last 20 years. Networks are composed of interlinked polyamide and polypropylene fibers. They are also referred to as nylon network barriers.

They are characterized by their light weight, ease of transport and convenient operation. The mesh size (number of holes per unit area) and the diameter of nylon fiber threads used to create the network should be determined by characteristics of the blown sand in the area. The diameter of the nylon fiber should be bigger in areas with coarser sand particles in wind-blown sand.

9.1.2 Mechanical sand releasing and transporting techniques

9.1.2.1 Sand releasing and transporting by shallow troughs

When constructing highway or railway roadbeds in sandy deserts, shallow, crescent-shaped troughs are made on both sides of the roadbed. These can be paved with gravel or stone to prevent erosion. To transport shifting sands, sand dykes or blocking sand dykes should be created in front of shallow troughs 30–40 cm higher than the nearby mobile dunes. When mobile dunes move closer to the front slope of the dykes, updrafts to dyke tops are formed between sand dunes and dykes. Suspended sand particles that are moved to the top of sand dune ridges are blown by this updraft directly to the top of the dyke. Wind-blown sand flows form on leeward slopes of the dykes and are lifted up over the shallow troughs between the dykes and roadbeds. This updraft blows sand particles over roads without any accumulation. To stabilize dyke surfaces, a 2 cm thick gravel or stone layer can be spread and then covered with asphalt (see below) to protect the dykes. The asphalt is normally 1–1.5 cm thick. Stone sheets can also be used to protect the dyke slope.

Ground observation shows that when the ratio of the arc length (l) and the maximum depth (h) (l/h) of the shallow trough is around 10–20, airflows create enough updraft to prevent sand accumulation on that portion of the roadbed.

9.1.2.2 Transporting sand with wind baffle boards

Use of wind baffle boards is a technique used to blow away accumulated sand and clean up the effects of drifting sand in a protected area by increasing the wind intensity behind the board. The wind baffle board is composed of studs, crossbars and grids (Fig. 9.1). The grid is normally made of timber, steel or other materials and helps to funnel wind. The board used to funnel wind should be installed on the upwind edge to blow away sand accumulated on the road. The effect of the wind baffle board is optimal when the road runs 45–90° to the main wind direction.

The height of the wind baffle board is directly proportional to the width of the protected section; the taller the board is, the larger the protected width will be. However, taller boards are more costly and inconvenient to construct. In addition, more sand will accumulate in front of the board. If the board is too low (less than 1 m), the ability to funnel wind is reduced, and the effective

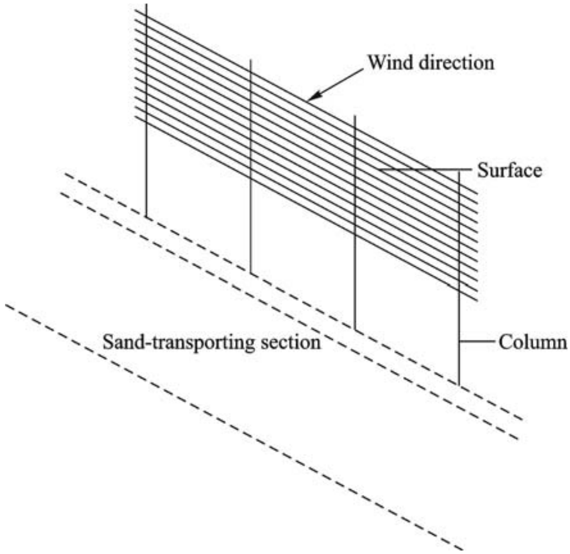

Fig. 9.1 Down baffling wind engineering to transport sands (Ci, 2002, with permission from author)

width for sand transport decreases. Studies indicate that the best height for the board is about 1.5–2.0 m. The height of the open space under the board is normally 1.2–1.5 m.

If the open space under the board is too small, the area of weak wind increases in front of the board, which results in sand accumulation. If the space is too big, the ability to funnel wind and release sand is weakened. The board used to release sand on the road is made of timber plates that measure 1.5 m high and 2 m wide. One hundred meters of board (about 50 plates) consumes 1.5 m^3 of timber. Boards should be connected to posts with a diameter of at least 10 cm. A 7 m length of wire can be used to tighten boards to the posts. One hundred meters of boards requires 3–4 m^3 of timber posts. If boards are made of metal plates, holes must be drilled in the metal plates to fix the boards to the network-shaped frame made of angle iron or flat iron. Metal posts should be buried, and then the metal plates should be screwed onto the metal posts. Metal boards are durable and effective but very costly.

Boards should be erected at an angle of ~70°–80° to the main direction of the wind. The metal posts are buried 1.5–2.0 m deep and extend 4.5–5.0 m above ground. The width of the metal board should be longer than the portion of sand accumulation on the road. Otherwise, some sand accumulation will occur along the two sides of the boards.

In addition to wind baffle boards, horizontal and vertical boards have proven useful (Fig. 9.2 and 9.3). The only difference between the designs of the two boards is their installation.

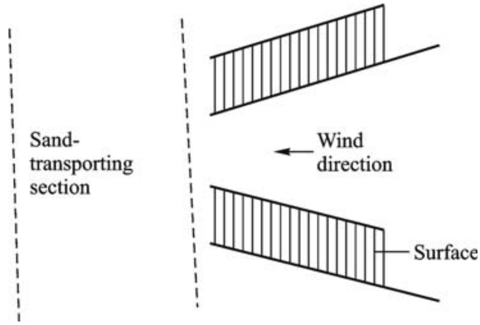

Fig. 9.2 Horizontal sand barriers (Ci, 2002, with permission from author)

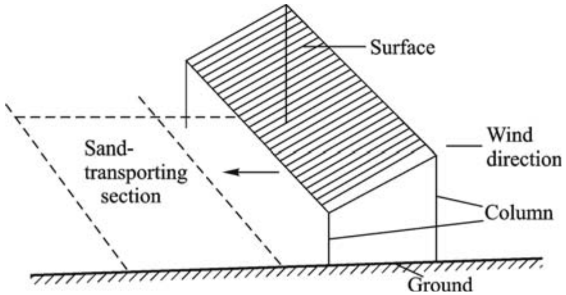

Fig. 9.3 Vertical sand barriers (Ci, 2002, with permission from author)

9.2 Mechanical sand barriers to control shifting sands

Mechanical barriers used to control shifting sands refer to measures to place various obstacles, made of wheat straw, hay, tree branches, clay, gravel, stone materials and sandbags, on moving sand surfaces. This technique is designed to change wind direction and velocity and to limit denudation and erosion. The nature of this technique is similar to the mechanical sand-blocking and sand transporting/sand-releasing techniques. Mechanical sand barriers have played a central role in controlling sand movement and dune stabilization in the sandy deserts of China. In regions with harsh environmental conditions, the mechanical sand barrier is the leading measure taken to control sand movement and stabilize dunes. In areas where conditions are less-harsh, the mechanical sand barrier is a necessary approach and ensures the success of biological approaches. During the past decades, practices for controlling sand movement and sand dune stabilization in China have shown that the mechanical sand barrier and biological approach are alternative solutions for fixing mobile dunes and stabilizing sand movement. Given the function of the mechanical sand barrier and its significant effects in sand stabilization and dune fixation, biological approaches will not replace mechanical barriers.

9.2.1 Types and principles of mechanical sand barriers

9.2.1.1 Types of mechanical sand barriers

Mechanical sand barriers can be classified into horizontal and vertical sand barriers according to sand control principles and different installation methods. Horizontal barriers can be classified into strip-installed and full-installed barriers. Vertical barriers can be classified into taller sand barriers (50–100 cm high over the sand surface), shorter sand barriers (semi-hidden sand barriers, 20–50 cm high over the sand surface) and hidden sand barriers (fully buried in the sand or only a small portion exposed on the sand surface). Vertical barriers can also be classified as ventilated, closed and unventilated types based on differences in their ventilation.

9.2.1.2 Principles of mechanical sand barriers for sand control

(i) Horizontal sand barriers: This type of barrier is designed to protect shifting surface sand from wind erosion. Mulch materials include straw, hay or grasses, stones and clays, emulsion asphalt and polyamide polypropylene fibers, and other chemical materials. These will prevent wind erosion from loose sand surfaces, which will not add more sand particles into the wind flows. However, this method is not very effective at catching sand particles in wind flows.

(ii) Vertical sand barriers: This type of barrier is mostly designed to accumulate drifting sand. Wind flow is disrupted by obstacles, and velocity is reduced. As a result, some sand particles or even sand drifts will be stopped, precipitate and accumulate around the obstacles. Vertical sand barriers are used along roads, communication lines and traffic facilities where shifting sand or sand drifts pass through.

(iii) Ventilated sand barriers: Scattered turbulence flows form as blown sand flows pass across the interspaces of this type of sand barrier. Friction increases, and kinetic energy is reduced as sand grains collide. The sand carrying capacity of the wind decreases as wind speed is reduced. Sand then accumulates both in front of and behind the sand barriers. Small amounts of sand accumulate in front of the sand barrier reducing the likelihood that the sand barrier will be buried. Large amounts of sand will be deposited behind the barrier which will stretch longitudinally and may extend for a long distance.

(iv) Unventilated or closed sand barriers: When blown sand flows pass through a sand barrier, they rise in front of the sand barrier and then immediately fall after passing through this type of barrier. Strong eddies will occur in front of and behind the sand barrier. The effects of eddies and sand particles colliding will cause wind velocity to decrease and the sand carrying capacity of the air current to weaken. Consequently, sand particles accumulate in front of and behind the sand barrier.

(v) Hidden sand barriers: A hidden barrier is a vertical sand barrier buried in the sand. The top of the barrier should be level with the sand surface or extend only slightly above the sand surface. This type of barrier does not affect blown sand flows above ground but stops the movement of sand across the ground surface. Hidden sand barriers control the base level of erosion. Although wind erosion will occur following installation of the hidden sand barrier, erosion process will not expand downward (Ding, 2007).

9.2.2 Technical criteria for designing sand barriers

9.2.2.1 Porosity of sand barriers

Usually, the ratio of the area of the open pores (or gaps) and the total area of the sand barrier is referred to as the porosity and is used as an indicator to measure ventilation performance. When the porosity is approximately 25%, sand accumulation in front of the sand barrier is two times the height of the barrier, and sand accumulation behind the sand barrier is 7–8 times the height of the barrier. When the porosity is 50%, almost no sand accumulates in front of the barrier, and sand accumulation behind the barrier is 12–13 times the height of the sand barrier. The smaller the porosity is the less sand accumulates behind the barrier. As a result, the sand barrier is quickly buried windward and its function to stabilize shifting sands is lost. On the contrary, as porosity increases, more sand is accumulated over a larger scale and the effective life for stabilizing shifting sands is longer. To achieve more effective sand control under local conditions, the size of the porosity should be determined based on wind speed and sand source. Usually, the ventilation performance with 25–50% porosity is reasonable. In regions with strong wind and less sand, the porosity should be smaller, but with more sand, the porosity should be larger.

9.2.2.2 Height of sand barriers

Under the same sandland conditions and sand barrier porosity, the amount of sand accumulation is directly proportional to the square of the height of the sand barrier. The height of a sand barrier is normally about 30–40 cm, and the maximum height is 100 cm.

9.2.2.3 Direction of sand barriers

Sand barriers should be installed at a right angle to the prevailing wind and normally erected on the windward slope of a sand dune. Before installing the barriers, a line should be drawn as a reference in the middle of the sand dune in the same direction as the prevailing wind. This is because the wind in the middle of the sand dune is stronger than at the two sides of the dune. Thus, the angle between the sand barrier and reference line should exceed 90°, but it should not exceed 100°. By doing so, the wind at the middle of the sand dune could shift to the two sides of dune. If the angle between the sand barrier and reference line is less than 90°, the air current is concentrated at the middle of the dune. Consequently, the sand under the barrier will be easily denuded or the barrier buried by shifting sands (Fig. 9.4).

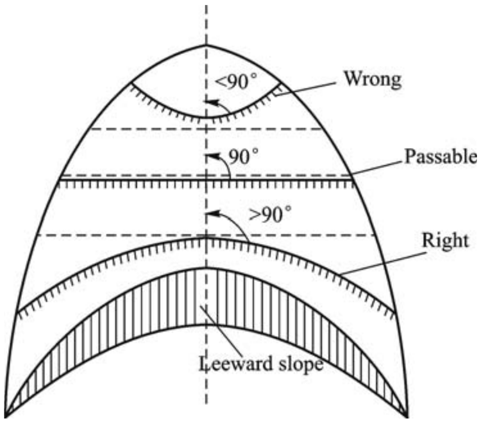

Fig. 9.4 Schematic diagram showing installation direction of sand barriers on windward slope (Ci, 2002, with permission from author)

9.2.2.4 Types and forms of sand barriers

Sand barriers are generally installed in row, network, herringbone, swallow wing and fish-bone shaped patterns. This section mainly describes rows and networks.

(i) Row-shaped installation: This kind of sand barrier is normally installed in the area where the prevailing wind is unidirectional. When the barrier is installed on the windward slope of a barchan dune, the top part of the dune should remain free of any barrier. The barrier should be erected along a barchan-shaped line. The barrier on barchan dune chains should be installed in arc shapes according to the shape of the barchan dune. Where two barchan dunes meet, wind funnels form resulting in severe denudation and frequent sand transport. Therefore, the distance between barriers should be small in these areas.

(ii) Network-shaped installation: This sand barrier is mainly used in sand areas with changing prevailing wind directions and strong side winds. Square network-shaped and rectangle network-shaped barriers should be selected based on wind direction.

9.2.2.5 Interspace between sand barriers

The interspace between barriers refers to the distance between two nearby barriers. When the distance between barriers is too large, the sand barrier is easily eroded and destroyed. If the interspace is too small, construction of the barrier will be too costly in terms of materials and manpower. Thus, the proper interspace between sand barriers should be reasonably determined before installation.

The interspace between barriers is related to the height of the sand barrier and the angle of the dune slope. Wind force should also be considered. High sand barriers should have large interspaces, and lower sand barriers should have small interspaces. The interspace should be small on dunes with steep slopes and large on dunes with gentle slopes. The interspace between sand barriers should be wide where wind is weak and narrow where wind is strong. On average, on a gentle dune with less than 4° slope, the interspace should be 15–20 times the height of the sand barrier. On undulating dune surfaces, the interspace should be calculated according to the height of the sand barrier and angle of the slope. The equation is:

$$D = H \text{ ctg } a \tag{9.1}$$

Where D is the interspace between sand barriers; H is the height of the barrier; and a is the angle of the dune slope.

The interspace of the clay sand barrier is 2–4 m, and the height of the barrier is 15–20 cm. Experiments show that the best design for a clay sand barrier in severely blown sand affected areas is a 1 m × 1 m or 1 m × 2 m square-shaped clay checkerboard. The amount of clay used for constructing a clay sand barrier should be determined by the barrier interspace and the size of clay bank. The equation is:

$$Q = 1/2\ ahs \cdot (1/c_1 + 1/c_2) \tag{9.2}$$

Where Q is the required amount of clay for constructing the clay sand barrier; a is the bottom width of the clay sand barrier; h is the height of the barrier; c_1 is the interspace between the clay banks vertical to the prevailing wind; c_2 is the interspace between the clay banks parallel to the prevailing wind; and s is the total area of the installed barriers.

9.2.2.6 Selection of materials for sand barriers

When selecting materials for constructing sand barriers, durable local materials that have lower costs and no negative effects should be considered. Normally, wheat straw, stones or gravel, tree branches and clay or hard soils from local sources are good options for barrier installation materials (Ding, 2007).

9.2.3 Methods for installing sand barriers

9.2.3.1 High vertical sand barriers

Materials: Tall grasses, reeds, tree branches and tall crop residues (such as corn stalks).

Installation methods: Bundle the sand barrier materials having a height of 70–130 cm, and then bury them along the designated lines and shapes on the dunes or sandland to a depth of 20–30 cm. The base of the barrier must be packed tightly, and a small, 10 cm sand ridge should be made at the base. Installation should be done following rainfall, as wet sandy soil is easier to compact.

9.2.3.2 Movable high vertical barriers

Materials: Timber plate and nails.

Installation methods: A closed vertical barrier is made of timber plates and installed in rows. The height is similar to the height of the high vertical sand barrier (70–130 cm). This barrier is movable and can be re-installed or moved at any time in response to a change in wind direction.

9.2.3.3 Semi-shallow straw barrier

Materials: Straw and other soft weedy materials.

Installation methods: Draw guidelines with lime, and then spread the materials (straw or weeds) evenly on the sand surface along the lines. Use a spade and hoe to press the straw 10–15 cm into the sand, and then compact both sides at the base.

9.2.3.4 Low clay sand barriers

Materials: Clay.

Installation methods: Installation guidelines should be marked on the surface before beginning. Clay should be placed along the lines. Make a small, triangle-shaped, 15–20 cm high clay bank. Be aware that any breach of these clay banks will cause denudation in strong winds.

9.2.3.5 Mulching sand barriers

Materials: Adhesive or hard-textured materials such as clay, gravel, brick, debris, colloid material and crude oil.

Installation methods: Spread mulching materials evenly on the sand surface with a thickness of 5–10 cm. Gravel should be spread evenly without open holes to protect the mulched surface from denudation.

9.2.3.6 Sandbag barriers

Materials: Nylon or fabric sandbags.

Installation methods: These sandbags must be made of durable materials treated with antioxidants and filled with sands so that each sandbag is about 10 cm thick. They are then installed on dunes to control sand movement and denudation. Bags are easy to stack, transport and install and can be reused many times. This technique has recently become popular and is often used with new materials.

9.2.3.7 Scattered mulching sand barriers

Materials: Tree branches, crop residuals and other plant materials.

Installation methods: These materials should be cut to the proper length and spread evenly on the shifting sand surface. This method is normally used in sand areas with low wind velocity and weak denudation or erosion potential.

9.2.4 Effectiveness of sand barriers

Vertical sand barriers play an important and effective role in stabilizing shifting sands. They are suitable for dune fixation in undulating sand areas with trich sand sources for from the protected areas. The disadvantage of this sand barrier is that it can cause sand accumulation around itself. Therefore, this vertical sand barrier should not be used to stabilize shifting sands nearby the protected areas. Moreover, this type of sand barrier needs a lot of manpower and materials and requires frequent maintenance after installation.

Clay sand barriers are low-cost with local materials and require little transport and manpower. This type of sand barrier has high water-holding capacity, which is helpful to plant growth, but is limited to regions where clay is available. Network straw checkerboards, wheat straw networks, sandbags and other sand barriers need sufficient local materials but are easier to use, are inexpensive and can cause a remarkable increase in surface roughness, a sharp reduction in wind velocity and significant effects in stabilizing shifting sands and mobile dunes.

9.3 Chemical measures for sand stabilization

The purpose of chemical sand stabilization is to provide a stable surface on the sand by spraying diluted cohesive chemical materials on the shifting sand surface. After treatment, water within diluted chemical materials quickly infiltrates into the deeper sand layer, while cohesive chemical materials remain in pores of the sand surface layer and congeal with sand particles to form a hard protective crust on the sand surface. Thus, air flows are restricted from contacting loose sand, and consequently, the sand surface is protected from wind erosion. This method can stabilize shifting sands in situ and cannot control sand particles within airflows. Chemical sand stabilization techniques are mainly used along communication lines and transport facilities in areas with highly mobile sands and around military bases and mineral and industrial sites in sandy deserts.

Chemical sand stabilization techniques have been used for 70–80 years; however, the chemical materials used today are much the same as those used during the 1930s and 1940s. Some chemical materials have been slightly improved upon with the addition of different compounds.

9.3.1 Asphalt emulsion for sand stabilization

Asphalts are black, organic, oil-based viscous material composed of 70–80% carbon, 10–15% hydrogen, 1–5% oxygen, 2–8% sulfur and 0.5–2% nitrogen, which are cohesive, waterproof (non-permeable and non-soluble) and resist corrosion. The physical and chemical properties of asphalt are more or less related to the proportion of oxygen, sulfur and nitrogen. The grade of asphalt is normally determined by its emulsible temperature (melting point), specific gravity and hardness.

Asphalt emulsion is composed of petroleum asphalt, emulsifier and water. Combined with emulsifier, it is a two-phased material diffused with asphalt into water. The asphalt particles are referred to as the diffusion phase, or internal phase, the water is referred to as the continuous phase, or external phase, and together this liquid is called oil-in-water emulsion. According to the electric charge of the liquid drops, the asphalt emulsion can be classified as a cation, anion, amphoteric ion or non-ion. According to the separation speed of asphalt from water upon touching sand particles, asphalt emulsion can be classified as quick separation, medium separation or slow separation.

The slow-separation asphalt emulsion, composed of HD-200/300 and HD-130/200 asphalts, is often used as a cohesive agent to temporarily stabilize the sand surface. The asphalt emulsion can remain on the sand surface for 2–3 years to control wind erosion and prevent denudation. Before spraying the asphalt emulsion, the sand surface should be watered to increase the depth of penetration of the asphalt emulsion. The depth to which asphalt emulsion will permeate into dry sand and wet sand is 10–15 cm and 20–30 cm, respectively. Asphalt emulsion will form a thin porous film (2–3 mm) on the sand surface. This film can be easily crimped and broken at the edges. Thus, the asphalt emulsion content should be no more than 10–15% while diluting the asphalt emulsion. Trampling by humans and animals should be avoided.

In addition, asphalt emulsion should be stored with a temperature not lower than 0 °C. To avoid dehydration, asphalt emulsion can be kept in an air-tight container. During long distance transport, 0.5 kg caustic soda should be added for every 10 tons of asphalt emulsion to avoid separation of the asphalt emulsion.

9.3.2 Asphalt compounds for sand stabilization

An asphalt compound is a type of dark-brown cohesive mixture containing asphalt or adhering oil, water and mineral powders (loess, loam soil, cement and lime). It is stirred in a cement mixer and can be directly sprayed onto the shifting sand surface with a mud pump.

9.3.3 Latex emulsion for sand stabilization

Latex emulsion is used to stabilize shifting sands by simply spreading over the sand surface. This latex emulsion can form a thin film with good elasticity. To stop shifting sands where wind velocity is approximately 6 $m \cdot s^{-1}$, 17.5 $g \cdot m^{-2}$ of latex emulsion should be used. When wind velocity is 10–12 $m \cdot s^{-1}$, the amount should be as high as 26.0–28.5 $g \cdot m^{-2}$.

9.3.4 Peat emulsion for sand stabilization

This method can be used in peat-rich areas of low-lying swamps among drylands. Treated peat emulsion can be used to stabilize shifting sands. The method to make peat emulsion is simple and can be widely used in peat-rich regions.

9.3.5 Adhesive agents for sand stabilization

This is an integrated method that has great potential to control shifting sand and is a simple method to agglomerate sand particles. Adhesive agents can be evenly sprayed on the sand surface to form a thin layer of integrated adhesive agents and underlying sand. The treated area should then be ploughed to break the agglomerated sand layer into small sheets that will withstand strong wind. These small sheets are effective at controlling wind and fixing sands. The latex can be used as the adhesive agent to create small sheets.

9.4 Hydraulic engineering measures to combat desertification

Hydraulic engineering usually involves various engineering works built to control and relocate surface water and ground water, to wisely use water resources, to alleviate potential flooding disasters and to promote local sustainable economic development. In recent decades, hydraulic engineering techniques have advanced rapidly, especially in arid and semi-arid regions in northern China where hydraulic engineering plays an important role in controlling water erosion and in mitigating and preventing blown sand disasters.

9.4.1 Storage and drainage engineering on slopes

Storage and drainage engineering on slopes refers to various water storage and drainage facilities constructed for controlling water erosion on slopes. The facilities function to harvest runoff on slopes for irrigation, to discharge surplus runoff, to protect slopes from erosion, to reduce sediment amount and to protect foothill farmlands. Storage and drainage engineering is usually designed and arranged together with constructed terraces and revegetation. The engineering should also be coordinated with the construction of irrigation channels, water ditches and road networks. At the same time, runoff interception ditches, drainage systems, canals, sedimentation ponds and water-storage ponds should be established.

9.4.1.1 Runoff-interception ditches on slopes

The purpose of runoff-interception ditches on slopes is to catch runoff on slopes. It shortens the slope length, cuts the runoff flow distance, reduces runoff erosion, harvests storm runoff on slopes and collects and transports the harvested runoff to a water storage dam or to irrigate farmland, forestland or grassland.

(i) Layout of the runoff-interception ditch

Runoff-interception ditches can be constructed on slopes less than 25° parallel with the contour and connected with drainage trenches perpendicular to the contour. The distance between ditches (distance on the slope) should be determined by the grade of the slope. The relationship between the grade of the slope and the inter-ditch distance is shown in Table 9.1.

Table 9.1 Slope grade and corresponding inter-ditch distance

SG	IDD	SG	IDD	SG	IDD
3	30	7	19	14–16	14
4	25	8	18	17–23	13
5	22	9–10	16.5	24–37	12
6	20	11–13	15	38–40	11.5

SG: Slope grade (%); IDD: Inter-ditch distance (m).

(ii) Design of the cross section of the runoff-interception ditch

The water volume (V) of each runoff-interception ditch can be calculated from the following equation:

$$V = V_w + V_s \tag{9.3}$$

Where V is the volume of the runoff-interception ditch (m^3); V_w is the runoff volume of one storm (m^3); and V_s is the soil erosion volume in 1–3 years (m^3). The metric unit for V_s should be calculated in cubic meters (tons) based on local soil bulk density.

In the above equation, V_w and V_s are respectively calculated:

$$V_w = M_w \times F \tag{9.4}$$

$$V_s = 3M_s \times F \tag{9.5}$$

Where F is the catchment area of the runoff-interception ditch (ha); M_w is the runoff modulus of one rainstorm ($m^3 \cdot ha^{-1}$); and M_s is the annual modulus of soil erosion ($m^3 \cdot ha^{-1}$).

The cross-section area of the runoff-interception ditch, A_1, can be calculated based on the value of V:

$$A_1 = V/L \tag{9.6}$$

Where A_1 is the cross-section area of the runoff-interception ditch (m^2); and L is the length of the runoff-interception ditch (m).

When the design of the cross-section is determined, the width and a safe height of the ditch dyke should be selected according to attributes of the building materials. The width of a small clay dyke should be no less than 0.3 m, and the safe height should be decided according to the volume of flow in the ditch. If the flow volume is less than 1 $m^3 \cdot s^{-1}$, the safe height should be 0.2–0.3 m, and if the flow volume is 1–10 $m^3 \cdot s^{-1}$, the safe height of the ditch dyke should be 0.4 m.

The runoff-interception ditch is normally built up in a half-digging and a half-filling manner as a trapezoid section. The bottom is 0.3–0.5 m wide, the depth of the ditch is 0.4–0.6 m, the inside slope is 1:1 and the outside slope is 1:1.5.

9.4.1.2 Drainage ditch on the slope

The drainage ditch on the slope is designed to drain surplus runoff, to control slope erosion and to reduce sediment transport. It is a ditch built on the two ends of the runoff-interception ditch or at the lower end of the runoff-interception ditch.

(i) Layout of the drainage ditch on the slope

The gradient of the drainage ditch on the slope can be determined by the location of the water storage pond or the natural water drainage route. When the location of the drainage outlet is at the foot of the slope, the drainage ditch can be perpendicular to the contour. When the location of the drainage outlet is on a slope, the drainage ditch can be built along the contour or crossing the contour. The ditch at the two ends of the terraced farmland should be built perpendicular to the contour and in the same direction as the road at the two ends of terraced farmlands. If the drainage ditch is made of clay or mud, drops should be set up at different parts.

(ii) Design of a drainage ditch on the slope

The cross-section of a drainage ditch on the slope is generally designed based on peak flow from an average rainstorm event. This can be calculated by the equation of uniform flow in the open channel as:

$$A_{\triangle} = Q/C \times (Ri)^{1/2} \tag{9.7}$$

Where $A_{\triangle}$ is the area of the drainage ditch cross-section (m^2); Q is the peak flow on the slope ($m^3 \cdot s^{-1}$); C is the Chezy coefficient; R is hydraulic radius (m); and i is the gradient of the drainage ditch.

i) Calculation of the Q value: The designed peak flow of a small catchment on the slope is calculated with a regional experience equation.

$$Q_P = KI^m F^n (F \geqslant 10\ \mathrm{km}^2) \tag{9.8}$$

$$Q_P = C_p F^n (1\ \mathrm{km}^2 < F < 10\ \mathrm{km}^2) \tag{9.9}$$

$$Q_P = C_p F (F \leqslant 1\ \mathrm{km}^2) \tag{9.10}$$

Where Q_P is the designed peak flow of an average rainstorm event ($m^3 \cdot s^{-1}$); K is an overall coefficient determined by ground surface slope, river network density, river course gradient, rainfall duration, watershed form and other elements; I is the net rainfall depth for an average rainstorm event (mm); M is an index relating peak flow to flooding flow; F is the catchment area of the slope drainage section (km^2); n is the decreasing index along with the increase of the catchment area; and C_p is the integrated parameter related to the given frequency.

ii) Calculation of the R value:

$$R = A_{\triangle}/x \tag{9.11}$$

Where x is the wetted perimeter of the drainage ditch (m), which refers to the total length of the water flow touching the ditch trough cross-section;

Rectangle cross-section: $$x = b + 2h \tag{9.12}$$

Trapezoid cross-section: $$x = b + 2h(1 + m^2)^{1/2} \tag{9.13}$$

Where b is the bottom width of the ditch (m); h is the water depth (m); and m is the coefficient of the inside slope of the ditch determined by the ditch depth and soil texture. This coefficient can be determined by referring to Table 9.2.

Table 9.2 The value of the coefficient (m) on the inside slope of the drainage ditch

Soil texture	Digging section			Filling section		
	(1)	(2)	(3)	(1)	(2)	(3)
Clay or loam soil	1.00	1.00	1.25	1.00	1.25	1.50
Slight loam soil	1.00	1.25	1.50	1.25	1.50	1.75
Sandy loam soil	1.25	1.50	1.75	1.50	1.75	2.00
Sandy soil	1.50	1.75	2.00	1.75	2.00	2.25

(1): Water depth <1 m; (2): Water depth 1–2 m; (3): Water depth 2–3 m.

iii) The C value: calculated with the Manning equation in most cases:

$$C = 1/n \cdot R^{1/6} \tag{9.14}$$

Where n refers to the roughness of the ditch, which is about 0.025 for earth ditches.

iv) The selection of the i value: The i value is determined by the topography and soil texture along the ditch, which is normally similar to the ground surface gradient. It is common to use 0.2–0.5.

The actual peak flow of the drainage ditch should be higher than the average peak flow, namely $Q \geqslant Q_{\mathrm{P}}$. Otherwise, the h, b, and i values should be readjusted, re-calculated and rechecked until the conditions are met.

9.4.1.3 Water-storage ponds

Water-storage ponds are built to make full use of runoff from slopes to mitigate effects of drought.

(i) Layout of water-storage ponds

Water-storage ponds are normally built at a low section or at the foot of a slope that is connected to the end of a drainage ditch or runoff-interception ditch to harvest runoff from the slope surface. The location and storage capacity of the ponds should be determined by the total volume of runoff harvested, the relationship between water storage and drainage and the eases of construction and water-use.

(ii) Water-storage pond design

The size, shape, area, depth and slope of the water storage pond can be designed according to the local landform and the total water-storage volume.

The total storage volume can be calculated according the following equation:

$$V = K(V_w + V_s) \tag{9.15}$$

Where V is the water storage of the pond (m^3); V_w is the runoff volume of an average rainstorm (m^3); V_s is the accumulated sediment volume (n years, m^3); and K is the safety coefficient (1.2–1.3). The values of V_w and V_s can be calculated according to the designed drainage volume and the sedimentation volume of the drainage ditch.

The intake and outlet areas of the ponds should be constructed of stone materials. The cross-section over which water flows can be checked by the equation of the rectangular broad-crested weir, namely:

$$Q = M \cdot (2g)^{1/2} \cdot bh^{3/2} \tag{9.16}$$

Where Q is the maximum flow volume of the intake or outlet ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$); M is the flow volume coefficient of 0.35; g is the gravity acceleration at 9.81 $\mathrm{m \cdot s^{-1}}$; b is the width of the broad-crested weir (m); and h is the water depth at the weir crest (m).

(iii) Sedimentation pond

To reduce the sediments in water-storage ponds, sedimentation ponds should be constructed at the upper part of the intake of water-storage ponds. The sedimentation pond should be rectangle shaped with a width two times wider than the drainage ditch and a length two times longer than its own width. The usual width of a silt-mud sedimentation pond is 1.0–2.0 m, the length is 2.0–4.0 m and the depth is 1.5–2.0 m. The intake and outlet of the sedimentation pond should be designed similarly to these of the water-storage pond and be made with stone materials.

9.4.2 Engineering in gullies and hilly valleys

Hydrological projects and facilities are built in valleys to stabilize valley banks, accumulate sediment, and control or alleviate flooding and debris flows. These facilities not only harvest runoff from rainstorms, control sediment accumulation and reduce soil erosion, but also slow down and reduce flood peaks and flood volume, increase water volume of a river and extend the life of the water-storage pond or dam.

9.4.2.1 Check dams

Check dams are normally constructed in small valley branches of a watershed, stream gully or canyon. The height of the dam is 3–5 m, and the sediment accumulation volume is less than 1,000 m^3.

(i) Types of check dams

Check dams can be classified depending on construction materials, permeability and duration of use. Classification based on construction materials includes earth dams, stone dams, *Salix* plantation dams, cement dams, reinforced concrete dams and wooden dams . Permeability includes permeable dams (stone and *Salix* plantation dams) and impermeable dams (earth and cement banks). Check dams based on duration of use include temporary dams (earth and stone dams) and permanent dams (cement and reinforced concrete dams).

(ii) Layout of check dams

Check dams should be small in size and widely distributed, starting at the upper part of the stream and then moving downstream. Check dams should be built one by one on the whole slope. A check dam should be located in the valley bottom with less than 5–10% gradient where the outlet is narrow and the upper stream is wider.

(iii) Check dam design

Design indicators of a bank include dimensions, distance between dams and spillway.

i) Dimensions

Table 9.3 shows the dimensions of common types of earth and stone dams.

ii) Distance between dams

The height of and distance between check dams are two interrelated and limiting parameters. When the height of the bank is well designed, the top of lower check dam is level with the bottom of the next higher check dam. This design is used to determine the inter-distance and number of dams, which will help avoid water inundation at the bottom of the higher check dam and will also increase the stability of the dam.

Table 9.3 Dimensions of check dams in northern China

Types	Dimensions of dam sections			
	Height (m)	Dam crest width (m)	Upstream slope	Downstream slop
Clay dam	2.0	1.5	1:1.2	1:1.0
	3.0	1.5	1:1.3	1:1.2
	4.0	2.0	1:1.5	1:1.3
	5.0	2.0	1:1.8	1:1.5
Mortarless pebble check dam	1.0–2.0	1.0–1.2	1:0.5∼1:1	1:0.5
Mortarless block-stone check dam	1.0–3.0	1.0–1.2	1:0.5∼1:1	1:0.5

The distance between dams can be calculated by the following equation:

$$L = H/(I - I') \tag{9.17}$$

Where L is the distance between the dams (m); H is the height of the dam (m); I is the original gradient of the valley bottom (%); and I' is the gradient of the dam filled up with sediment (%). Usually, the gradient of coarse sands (with gravel or stone) is 2.0%, the gradient of clay is 1.0%, the gradient of loam is 0.8% and gradient of sandy soil is 0.5%.

iii) Spillway

To avoid destruction of the check dam by severe floods, a spillway for stone check dams should be made in the middle section at the top of the dam. The spillway for an earth dam should be built on hard earth or bedrock at one side of the dam. The spillways of the two nearby check dams should be built, if possible, in different locations of the dams.

9.4.2.2 Sediment storage dam

Sediment storage dams are normally installed in main valleys or large valley basins to block sediment, to reduce flooding and to control debris flow to downstream areas. The height of the dam should be over 5 m, and the sediment storage volume should be over 10–100 m^3.

(i) Types of sediment storage dams

i) Stone dam

Stone dams include mortarless stone dams and mortar stone dams. A mortar dam is a gravity dam with a simple structure and is one of the most widely used dams. It is trapezoid-shaped with an upstream slope of 1:0.5 and a downstream slope of 1:0.2. Mortarless stone dams are also trapezoid-shaped and are suitable for small flood gullies.

ii) Mixed dam

According to the materials used, mixed dams can be classified as earth-stone mixed dams and wood-stone mixed dams.

The dam body of an earth-stone mixed dam is filled in with earth, mud or clay, but the top and bottom of the dam is built with mortar stone. The dam is trapezoid-shaped. When the height of the dam is 5–10 m, the upstream slope is 1:1.5–1:1.75, the downstream slope is 1:2–1:2.5 and the width of the dam top is 2–3 m. To prevent water leakage from the dam body, clayey and waterproof layers should be built on the upstream slope of the dam, and drainage pipes should be installed at the foot of the downstream slope. An earth-stone mixed dam is used in regions where there are little stone materials but plentiful earth resources.

The dam body of a wood-stone mixed dam is built with a framework of wood pillars about 0.1 m in diameter, which is filled with stones and rocks. The top of the dam and upstream slope are always built with mortar stone to prevent them from being destroyed by floods. This dam is used in regions with rich timber resources.

iii) Arch-shaped dam

An arch-shaped dam is built with mortar stone or concrete, and the body is arch-shaped. The two sides of the dam are built on hard bedrock. Pressure from floods and sediment on the upstream side of the dam is mostly absorbed by rocks at the two sides of the dam body. The remaining pressure is transferred to the dam bottom. The arch-shaped dam has a high capacity to resist pressure because of the mortar stone and concrete building materials. Therefore, the thickness of the dam body can be slightly reduced. This dam uses less manpower and inexpensive building materials. It is estimated that about 25–30% building materials will be saved compared to constructing other types of similar-sized dams. This dam is suitable in regions with a narrow valley and riverbed and rocky side slopes.

iv) Grid-shaped dam

The grid-shaped dam is a new type of sediment storage dam that has been developed in recent decades. It has good permeability and can selectively block sediments. Constructing this dam uses less manpower and can save 30–50% on building materials compared with other dams. There are several kinds of grid-shaped dams, including concrete grid-shaped dams and metal grid-shaped dams.

(ii) Sediment storage dam height

Generally, the higher dam is the more sediment it accumulates. However, a higher dam body is more expense. Small sediment storage dams are 5–10 m high, medium dams are 10–15 m high and large dams are over 15 m high.

(iii) Sediment storage dam design

Dimensions. Table 9.4 lists dimensions of a mortar stone dam.

Stability calculation. There are many stresses acting on the body of the dam, such as the weight of the dam, sediment weight, water pressure and force of impact from mudslides and earthquakes . By calculating these acting forces, the most severe combination of acting forces is used to calculate stress and anti-sliding stability to guarantee that the dam is built to withstand these external forces.

Table 9.4 Dimensions of a mortar stone dam

Dam height (m)	Dam crest width (m)	Dam bottom width (m)	Upstream slope	Downstream slope
3	1.2	4.2	1:0.6	1:0.4
4	1.5	6.3	1:0.7	1:0.5
5	2.0	9.0	1:0.8	1:0.6
8	2.5	16.9	1:1	1:0.8
10	3.0	20.5	1:1	1:1.8

Calculation of spillway. The shape of the spillway is usually trapezoidal. The side slopes are 1:0.75–1:1. An arch shape is the best design for the debris flow gullies with rich solid materials.

Downstream energy consumption facilities. Water overflowing the top of the dam has a large amount of energy. It is possible that the base of the dam and the riverbed downstream can become severely eroded and deformed. Thus, solutions to dissipate this energy must be offered. These solutions include subsidiary dams (side dams) and aprons. Subsidiary dams are suitable for floods and debris flows in large and medium valleys. This energy-dissipation facility is composed of one subsidiary dam to reduce the energy of floods and debris flows. The top of the subsidiary dam should be 0.5–1.0 m higher than the bottom of the upstream sediment storage dam to guarantee that the height of sediments in the subsidiary dam is higher than the bottom of the main dam. The distance between the subsidiary dam and the main dam should be 2–3 times the height of the main dam. The apron is only suitable in small valleys or gullies and is normally built with mortar stone. Its length is 2–3 times the height of the main dam.

9.4.2.3 Silt storage dam for farmland formation

A silt storage dam is built in a valley to block sediment and form farmland. It is used to deter floods, block silt and level farmlands in line with objectives for the development of agriculture, forestry and fruit production. The silt storage dam is an important solution used in integrated rehabilitation of small watersheds.

(i) Structure of the silt dam

A silt dam is composed of the dam body, spillway and water release works (Fig. 9.5). The dam body is used to block floods, accumulate sediments and heighten the floodplain terrace. The spillway is used to drain and spread flood waters. When it overtops the designated water height, floodwater drains through the spillway to guarantee safety of the dam body and formed farmland. Water release works usually consist of vertical wells and horizontal pipes.

These structures are used to drain clear water from the dam.

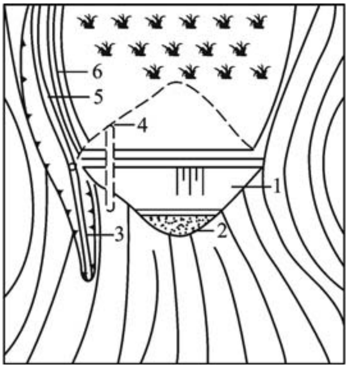

Fig. 9.5 Diagram of silt storage dam

1—dam body; 2—water drainage body; 3—spillway; 4—vertical well; 5—horizontal pipes; 6—flood prevention bank

(ii) Types of silt storage dams

Small silt storage dam: 5–15 m high; storage capacity is 10,000–100,000 m^3; catchment area is less than 1 km^2. This dam is normally built in small branch gullies and upstream of medium branch gullies.

Medium silt storage dam: 15–25 m high; storage capacity is 100,000–500,000 m^3; catchment area is 1–3 km^2. This dam is normally built downstream in large branch gullies or upstream of or in middle stream sections of main gullies.

Large silt storage dam: over 25 m high, storage capacity is 0.5–5 million m^3; catchment area is 3–5 km^2 or more. This dam is mostly built in the middle or downstream of main gullies or downstream of large branch gullies.

(iii) Dam system layout

The dam system refers to the construction of a series of silt storage dams along one valley. The density of dams should be determined by the precipitation, gully gradient, gully density, local conditions at construction sites and advantages and disadvantages of development. Three to five dams per km^2 is a suitable density in the hilly-gully region of the Loess Plateau, which has a gully density of 5–7 $km \cdot km^{-2}$ and a gully gradient of 2–3%. In the relic tableland gully region of the Loess Plateau, which has a gully density of 3–5 $km \cdot km^{-2}$, dam density is 2–4 dams per km^2. In earth-rocky mountainous regions, it is reasonable to construct 5–8 dams per km^2.

(iv) Locations of dam sites

Basic requirements for a good dam site location include high water storage and land formation capacity, low construction costs and good security. The following points should be considered when selecting dam sites: (i) the dam site should be placed in a narrow and deep gully with large water-storage capacity, and the bottom of the valley should be wide and level; (ii) topographic and geologic conditions adjacent to the dam site should be suitable for constructing the spillway; (iii) materials for constructing the dam should be easy to obtain and easy to transport to the dam site; (iv) the geologic structure of the dam site must be stable. Loose earth and landslides are unfavorable for dam construction; (v) the location of the dam site should not be in valley basins, bends, spring wells or waterfalls; and (vi) to reduce overflow costs, the overflow area of the dam should avoid villages, cultivated lands, transportation facilities and mineral sites.

9.4.3 Floodwater and debris flow discharge engineering

9.4.3.1 Floodwater and debris flow discharge ditch

Floodwater and debris flow discharge ditches can be classified into three different types, namely, digging-filling discharge ditch, lime-sand-clay mixed-earth discharge ditch and mortar stone discharge ditch. Selecting an appropriate discharge ditch is primarily based on the nature of the gullies. The digging-filling discharge ditch is the easiest to make and is suitable in debris flow gullies. The mixed-earth discharge ditch is suitable for high sediment-carrying flood gullies. The mortar stone discharge ditch is suitable to narrow river courses where flood scouring is strong and water flow is rapid. The design of the floodwater and debris flow discharge ditch must ensure smooth drainage without sedimentation or flood-scouring.

9.4.3.2 Sedimentation basin

The sedimentation basin is designed to block sediments and stones. The following points should be considered when designing and installing the basin: (i) it can be constructed in valleys where slopes are steep, slope erosion is serious and flood and debris flow are frequent; (ii) it can be built in gully sections with gentle slopes; (iii) the sedimentation basin cannot be installed in sections where deposition is severe and debris flow will potentially threaten farmland, settlements or livelihoods; and (iv) when the sedimentation basin is filled with sediments and stones, a new sedimentation basin should be installed at a new location.

The capacity of a sedimentation basin is based on the quantity of silt-mud that would occur in 1–2 floods per year. When designing the capacity of the sedimentation basin, the geologic and topographic conditions, angle of the slope and vegetation of the valley should be surveyed.

The simplest design of a sedimentation basin is a wide gully section. All gully slopes should be protected with stone materials. Horizontal mortar stone wings are needed at the intake and outlet of the sedimentation basin. The upper and low parts of the gully beyond the sedimentation basin should be maintained at their original heights.

9.4.4 Irrigation engineering

In the arid and semi-arid regions of northern China, an integrated irrigation system includes:

(i) Water storage facilities: Reservoirs, catchments, silt storage dams or water-storage ponds that block and store river water or runoff are water storage facilities.

(ii) Water intake facilities: Referred to as channel head facilities, water intake facilities draw water from a river or a reservoir, or they pump underground water according to the condition of irrigation water supplies.

(iii) Water channeling facilities: All levels of channel systems that transport and distribute water to cropland are included, such as the main trunk channel, trunk channel, branch canal, lateral canal and field ditch, as well as water troughs, sluice gates and tunnel and waterfall slopes. Underground pipe facilities for irrigation purposes is also a necessary part of water channel facilities.

(iv) Irrigation ditches in field patches: Irrigation ditches in field patches include the sub-lateral canal, irrigation trench, small facilities along the channel stops and the pipe and devices for water-saving irrigation. These ditches or devices are necessary to distribute water to cropland and guarantee plant growth.

(v) Flood control and drainage facilities: Flood control and drainage facilities refer to all types of spillways, sluice gates and drawing flood facilities that protect channel and canal systems during flood seasons. They also include on-site and underground drainage systems that drain surplus water in fields.

Water-storage facilities and flood control and drainage facilities have been introduced above. Three other facilities are introduced as follows.

9.4.4.1 Water intake facilities

(i) Water channeling facilities

i) Water channeling without a dam: Facilities include the intake gate, sluice gate, scouring sluice and water diversion dykes. These facilities are normally used at the middle and upstream areas of rivers where water volume is sufficient, water level is stable and the topographic conditions are unsuitable for constructing a dam. Hetao irrigating areas channeling water from the Yellow River in Ningxia and Inner Mongolia use this method.

ii) Water channeling with a dam: Facilities consist of a cross-river dam, an intake gate, a sluice gate and flood control dykes. The dam is generally installed at a section with a narrow river course and good geologic conditions that reduce the costs and workload and also increase the stability and safety of the dam facilities and structures. This method is frequently used to pump, channel and draw water at the upper and middle reaches of the river or in mountainous and hilly regions.

(ii) Water pumping facilities

Water pumping facilities are hydraulic facilities that pump irrigation water to regions where flood irrigation is limited or where flood-irrigation systems are not economical. They consist of a pumping station and its affiliated facilities.

i) Site selection for the pumping station

The site for the pumping station should meet the following requirements: ① open topography; ② a solid foundation; ③ available electricity, ④ a reliable water supply; and ⑤ convenient transportation in a settled area. High elevation and large irrigation areas need multi-stage water pumping. The height of each pumping station should be determined based on the minimum amount of power needed and then be readjusted and corrected according to topographic conditions.

ii) Designed water flow and pump-lift height

The designed water flow can be determined by tracking the maximum irrigation flow during a continuous time period (from 2–25 days) in the process of water consumption in an irrigation system. Generally, the maximum ration for each irrigation event can be used to calculate the designed water flow of the pumping station. The designed pump-lift height of the pumping station can be calculated by the average actual pump-lift height plus water loss in the pipelines and canals.

iii) Pump selection and its affiliated facilities

The following principles should be considered when selecting a water pump: ① meeting the requirements of the water flow volume and pump-lift height; ② ensuring efficient and reliable operation of the pumping station; ③ the economic investment; ④ the convenience of maintaining and managing the pump; and ⑤ the convenience of integrated utilization.

The engine should be selected first. In regions without sufficient electricity or those that lack electricity, an internal combustion engine should be selected. However, sometimes natural energy sources can be used to drive small water pumps, such as solar, wind turbine and hydraulic energy.

(iii) Underground water uptake facilities

i) Types of underground water uptake facilities

Underground water uptake facilities in soil erosion regions of northern China include pipe wells, barrel wells, Karez wells, radiating wells, multi-pipe wells and subsurface water interceptors.

The pipe well: The tube well is the most popular well used to pump water from underground. It can be used to exploit deep or shallow underground water. The pipe well is mainly composed of a series of pipes, and water is pumped by mechanical force. Thus, it is also called a motor-pumped well. The pipe well consists of a well-head, side-wall pipes, filter pipes and silt-up pipes. Different pipes made of different materials are suitable for different wells of various depths. The steel pipe is suitable for a deeper well, and iron pipe is suitable for a well with a depth of no more than 250 m.

The barrel well: The barrel well is a large-caliber, vertical pumping well and is 1–5 m or more in diameter. It is suitable for exploitation of shallow underground water with a depth of 6–20 m. It is particularly feasible to use a shallow barrel well with a large caliber in aquifer layers with poor permeability in mountain areas. The barrel well is built with mortar brick or stone, and some are built with reinforced concrete. The barrel well has a simple structure, is convenient to maintain and uses indigenous materials. Due to limitations in depth, the barrel well can draw a small amount of water from underground. If there is an increase of water in thick aquifer layers or phreatic water layers, drilling should continue, and pipes should be installed at the bottom of the barrel well into the deeper layer to draw the phreatic water. This kind of well is termed a pipe-barrel well.

Karez well: The Karez well is a popular well used anciently in the arid Xinjiang region of western China. The Karez well (also known as the qanat well) is characterized by a horizontal ditch stretching from piedmont aquifers to lowlands where underground water then flows spontaneously to the surface. The Karez well is normally built at piedmont alluvial-proluvial fan areas. It consists primarily of open canals, underground canals (corridors), vertical wells and cisterns. There is a vertical well every 20–30 m, and the vertical well and underground canals are linked. The wellhead is oblong and 1 m long and 0.7 m wide. There are several tens or several hundreds of vertical wells in each Karez well system. There are several tens of meters of open canal at the outlet of the underground corridor of the Karez well, and the cistern is constructed for storing water at the end of the open canal. The length of the Karez well is at least 3 km, and the maximum length is usually 20–30 km.

Radiating well: When the permeability of the aquifer layer is poor and the water-drawing volume is insufficient, horizontal water pipes should be installed in aquifer layers surrounding the original vertical well to increase the water-drawing area and volume. Because the pipes radiate horizontally into aquifer layers, it is termed a radiating well. The well consists of a vertical collector well and many horizontal radiating pipes. The lengths of the radiating pipes vary from several tens to several hundred meters, and they are usually 50–200 mm in diameter. Through the radiating pipes, underground water flows into a collector well. The radiating well has a large area for collecting water and a large capacity for drawing water. The water-drawing volume per individual well measures as high as $1\ m^3 \cdot s^{-1}$. This well is especially suitable for drawing water out of loess layers.

Multi-barrel well: The multi-barrel well is a new type of well that pumps underground water and combines special characteristics of the radiating well and the steel-pipe well. Several plastic pipes (30–40 mm in diameter) fitted with filter devices are equidistantly buried in aquifer layers in circles. They are linked with collecting water pipes in a radial pattern and are then connected with the water pump. Because of the short pipes, this well is suitable for exploitation of shallow water. This well is simple in structure, light weight, has considerable water-drawing volume and is cost effective. It is popular in sandy areas in the north of Shaanxi Province.

Subsurface interceptor: leakage has become a serious problem due to sand, gravel and stone sedimentation in medium and small river streams in rocky mountainous areas. At times other than the flood season, water flow is limited in these rivers. Most water infiltrates the soil and flows away under the riverbed. On these river courses, subsurface interceptors are constructed to retain underground water flow for irrigation purposes. This is termed a subsurface interceptor. A subsurface interceptor facility consists of an intake facility, water transporting pipes, collector wells (pools), checking wells and intercepting walls (intercepting dams).

ii) Distance and number of irrigation wells

When the exploitation and recharging volumes of underground water are basically balanced, the water-pumping volume of the individual well and the irrigation area determine the distance between irrigation wells. The radius of the irrigation circle is used to decide the distance between wells. The distance (D) between wells can be calculated with the following equation:

$$D = (667QtT\eta/m)^{1/2} \tag{9.18}$$

Where Q is the water-pumping volume of an individual well ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$); η is the effective utilization coefficient of irrigation water; m is the quota of irrigation water; t is the number of irrigation hours of the well per day; and T is the number of required days for completing one irrigation cycle for the controlled irrigation area.

In regions with insufficient water supplies, when the recharge volume of the underground water cannot meet irrigation requirements, the number of wells and the distance between wells in a unit area can be determined according to the allowable exploitation modulus of aquifer layers and the water pumping volume of each well. The number of wells in a unit area can be calculated by the following equation:

$$N = \varepsilon/QtT \tag{9.19}$$

Where N is the average number of wells per km^2; ε is the allowable exploitation modulus ($\mathrm{m}^3 \cdot \mathrm{km}^{-2} \cdot \mathrm{a}^{-1}$); Q is the water-pumping volume of each well ($\mathrm{m}^3 \cdot \mathrm{h}^{-1}$); t is the working hours of the well per day; and T is the annual number of working days of the well.

The distance between wells (D) is:

$$D = 1\ 000(1/N)^{1/2} = 1\ 000(QtT/\varepsilon)^{1/2} \tag{9.20}$$

9.4.4.2 Water channeling facilities

Water-transporting canals for irrigation can be divided into several types based on topographic condition and the number of acres requiring irrigation. They include main canals, branch canals, lateral canals, field ditches and sub-lateral canals. To meet requirements necessary to transport and distribute water, a water distribution system also consists of a bifurcation gate, check gate, sluice gate, aqueduct, cascade, inverted siphon, water scale and other affiliated facilities. These should be installed and constructed along the water-transporting canals. At present, in arid and semi-arid areas that have characteristically low water supply and high losses from leakage, a mixed water-transport system should be gradually adopted. Main and branch canals should use open canals, and lateral canals and field ditches should use pipeline.

(i) Selecting canal and ditch systems

Main canal: The typical design is composed of a main canal installed along a contour and a branch canal vertically installed along a contour line and separated at the lower side of the main canal. Another design has the main canal vertically installed along the contour, when topography is backbone-shaped with laterals slanting toward the two sides. The branch canals are separated from the two sides of the main canal.

Branch and lateral canals: These canals draw water from main canals and redistribute it to the end users. Installation of branch and lateral canals should allow easy distribution of water, convenient irrigation, unblocked drainage, proper cultivation and sound cropland management. The distance between branch canals should be 2,000–3,000 m. In irrigated areas of plains, the natural landscape should determine the amount of acreage lateral canals can irrigate. The average irrigated land area is 200–300 ha and can be as high as 466.7–666.7 ha in some regions. But in mountainous areas, the amount of irrigated land varies, as do the length and distance between lateral canals. These distances should be fixed according to the landscape and topography and be based on site-specific needs and conditions.

(ii) Canal section design

A U-shaped canal is a popular open canal with low leakage. It is characterized by high hydraulic efficiency, smooth and rapid flow of water and high capacity to transport both water and sediment. Compared with the trapezoid canal, loss from transporting water in the U-shaped canal is reduce by 3.7% per km. Compared with the earth canal, loss due to water leakage in the U-shaped canal is reduced by 97% per km.

The trapezoidal canal is also another open canal with low leakage. It is characterized by high hydraulic efficiency, rapid water flow, even distribution of water, ease of restoration after freeze-thaw processes, less farmland occupancy and low costs of manpower and materials. The design of this canal is suitable for large and medium low-leakage canals or channels.

(iii) Facilities associated with canals and ditches

i) Facilities for regulating and allocating water volume

The accessory facilities constructed on the irrigation canal for regulating the water table and distributing water flow volume include the check gate, bifurcation gate and sluice valve (sluice gate). The bifurcation gate is a facility that draws water from the main canal to the branch canals. The sluice valve is installed at the intersection of the branch canal and lateral canals and controls and distributes the volume of water flow.

ii) Crossed facilities

Crossed facilities are the specific water-channeling devices, such as a tunnel, aqueduct, inverted siphon and culvert, built to cross streams, valleys, transport lines and roads or even over a hill ridge (using an inverted siphon).

iii) Waterfall related facilities

These facilities, including the declivity and cascade, are constructed at the center of a waterfall.

iv) Water discharge facilities

These facilities, including the spillway discharge dam and discharge sluice gate, are built for clearing remaining water in the canal when the irrigation system is under threat of damage.

v) Sediment-washing and sediment-accumulating facilities

These facilities are built at the head of the canal or in a channel system to reduce sediment accumulation within the canal system. They include the sediment-washing gate and sediment-accumulating sedimentation ponds.

vi) Water-measuring facilities

These are measuring devices installed along the canals to accurately control water drawing at different levels and to charge water fees. They include water gauges, water-measuring troughs, water measuring valves and water meters.

(iv) Low-pressure water pipe system

A low-pressure, water-transporting pipe system can be used to replace a water-transporting open channel. With a certain amount of pressure, water is led and distributed to crop fields via bifurcation gates and water pipes. The maximum working pressure of the water pipe is generally no more than 0.2 MPa, and the pressure at the farthest outlet of the pipe is 0.002–0.003 MPa. The low-pressure water pipe irrigation system is characterized by ① large water volume at the outlet and rapid water transporting; ② low leakage and evaporation; ③ high water use coefficient; and ④ no limitations due to topographic conditions. At present, the low-pressure, water-transporting pipe system is widely used in well-irrigated areas in China where ground water is the main water source.

9.4.4.3 Irrigation ditches in field patches

Irrigation ditches in field patches refer to the end water transporting facilities that are distributed within fields. It includes all fixed or temporary irrigation ditches and accessory facilities at various levels within the field patches. The field ditches usually run parallel with the road and at right angles to the higher-class canals. Crop fields should be kept square-shaped and similarly sized for convenience in cultivation.

In plains, the irrigation area of the field ditch is normally 33.3 ha, and the distance between field ditches should be 300–600 m. In mountainous or hilly irrigated areas, because of small distances between and irrigation areas of lateral canals, sub-lateral canals can be opened along lateral canals. Installation of a field canal is unnecessary.

9.4.5 Runoff-harvesting engineering

Runoff-harvesting engineering is a kind of micro-water conservation project, which is effective at harvesting, storing and using surface runoff in arid, semi-arid and other regions without sufficient water supplies. Runoff-harvesting engineering normally consists of the runoff-harvesting system, water transporting system, water purification system, water storage system and irrigation system (Wu, 2002; Li et al., 2005; Wu and Feng, 2009).

9.4.5.1 Runoff-harvesting system

The main component of a runoff-harvesting system is a micro-catchment with a treated or untreated surface. The untreated micro-catchment is a naturally-formed or built area with high runoff rate and low infiltration rate, such as villages, settlements, yards and roads. The treated micro-catchment refers to man-made ground specifically for runoff collection (Li et al., 2005).

(i) Treatment methods of catchment surfaces

First, existing natural or man-made landscapes and topography, such as asphalt roads, house roofs and household yards, and original slopes can be chosen to harvest runoff. If existing areas are unable to collect enough runoff to meet needs, new artificial harvesting areas should be constructed as subsidiary harvesting areas. Common materials used to treat artificial runoff harvesting surface include concrete, cemented tiles and plastic films. At present, new materials, such as HEC soil-solidified agent, anti-infiltration films and cloths are widely used for harvesting runoff. The results of different materials vary widely in collecting surface rainwater and runoff. They should be carefully selected considering topographic conditions and the surrounding landscape. Table 9.5 and Table 9.6 show the runoff harvesting efficiency of different treatment materials in Gansu, Ningxia and Inner Mongolia.

(ii) Preparation of the micro-catchment

Concrete micro-catchment: Before construction, the surface of the micro-catchment should be watered, and the top 30 cm of soil should be turned over and then compacted. The bulk density should not be lower than 1.5 $t \cdot m^{-3}$. On areas without other special requirements, concrete can be directly applied to the ground. On areas with additional special requirements, such as threshing ground or roadways, concrete should be paved with the project design.

Roof tile micro-catchment: House roofs are usually used as micro-catchments. The water-harvesting efficiency of cemented tile is 1.5–2 times higher than that of machine-made or hand-made earth tiles. The harvested runoff is often used for garden irrigation or for domestic use. A slanted earth slope can also be constructed simulating a house roof, and cemented tile can be used as the water-harvesting surface. Tiles should be tightly cemented to eliminate water leakage.

Table 9.5 Runoff harvesting efficiency of catchment treated by different materials in Gansu and Ningxia ($m^3 \cdot m^{-2}$)

Mean annual rainfall (mm)	Con	CeT	CeS	PlF	MMT	CLT	CLS	APR	OrS
400–500	0.80	0.75	0.53	0.46	0.50	0.40	0.25	0.68	0.08
	0.79	0.74	0.25	0.45	0.48	0.38	0.23	0.67	0.07
	0.76	0.69	0.41	0.3	0.39	0.31	0.19	0.65	0.06
300–400	0.80	0.75	0.52	0.46	0.49	0.40	0.26	0.68	0.08
	0.78	0.72	0.46	0.41	0.42	0.34	0.21	0.66	0.07
	0.75	0.67	0.40	0.34	0.37	0.29	0.17	0.64	0.05
200–300	0.78	0.71	0.47	0.41	0.41	0.34	0.20	0.66	0.06
	0.75	0.66	0.40	0.34	0.34	0.28	0.17	0.64	0.05
	0.73	0.62	0.33	0.28	0.30	0.24	0.13	0.62	0.04

Con: Concrete; CeT: Cement tile; CeS: Cement soil; PlF: Plastic film; MMT: Machine-made tile; CLT: Clay tile; CLS: Compacted loess soil; APR: Asphalt paved road; OrS: Original slope.

Table 9.6 Runoff harvesting efficiency of catchment treated by different materials in Inner Mongolia ($m^3 \cdot m^{-2}$)

Mean annual rainfall (mm)	Waste slope	Hard road	Mixed soil road	Cemented road	Plastic film
200	0.066	0.077	0.088	0.091	0.103
250	0.074	0.086	0.099	0.105	0.116
300	0.103	0.120	0.137	0.145	0.161
350	0.109	0.127	0.145	0.154	0.170
400	0.137	0.160	0.182	0.194	0.214
450	0.215	0.250	0.286	0.304	0.336

Sheet stone (or gravel) cemented micro-catchment: Different cementing methods should be adopted depending on the sizes and shapes of the stones or gravel. If stones are sheet-like and regularly shaped, they can be placed horizontally on a compacted 30 cm thick surface. If stone or gravel materials are small and irregularly shaped, they can be vertically paved or inserted into soil. The gravel layer should be at least 5 cm deep.

Earth micro-catchment: In rural areas, an earth road can be used to harvest runoff after it is smoothed and leveled. If natural sloping areas are used to harvest runoff, the slope surfaces should be wetted, turned over to a depth of 30 cm and compacted. The bulk density should be higher than 1.5 $t \cdot m^{-3}$.

Plastic film micro-catchment: There are two methods using plastic films to harvest water, namely exposed and hidden methods. The exposed method directly covers the plastic films on a well–prepared, sloping land surface. A heating iron is used to connect 10 cm of overlapping plastic film, or 30 cm of overlapping film should be folded to limit water infiltration along connected seams. The hidden method applies plastic film on a smoothed, compacted surface, which is then covered with 4–5 cm of mud or fine sand. The mud should be evenly applied and compacted. Fine sand should be evenly paved on the slope surface and compacted. The compacted surface should not be trampled. Appropriate locations of the micro-catchment should be stabilized with bricks, stones and wood materials.

9.4.5.2 Water-transporting system

The water-transporting system refers to the ditches, canals or water blocking ditches that transport runoff harvested from the micro-catchment into the water purification system.

The design and installation of water-transporting system differs because of differences in topographic condition, micro-catchment locations and surface treatment materials. If the distance from the runoff harvesting system to the water-storage system is relatively long, permanent canals or ditches such as U-shaped or rectangle-shaped cemented ditches should be installed. If highways and roads are used as runoff harvesting sites, the affiliated drainage ditches along the highways and roads can be used to connect with the water transporting ditches or canals to bring the water to the storage dam. These drainage ditches should be treated with measures to reduce infiltration. During water-collecting periods, these ditches or canals should be cleaned periodically to remove litter and sediments. When using a mountain slope as a runoff-harvesting site, runoff-interception ditches should be built along the contour every 20–30 m, and the runoff flowing distance on these slopes should be as short as possible to reduce infiltration. The runoff-interception ditch can be made with soil, and the gradient of the slope should be 1:30–1:50. The runoff-interception ditch should also be linked with the water-transporting ditch at a right angle. The U-shaped or rectangle-shaped canals should be built with cement or with brick and stone materials.

9.4.5.3 Water purification system

All harvested runoff must be filtered and treated before it is transported to a water storage pond or dam. Filtering or treatment removes and collects silts and other wastes. The purification devices often used in front of the water pond or dam are sedimentation ponds and filter fences.

(i) Sedimentation ponds

The sedimentation pond is normally built about 3 m away from the water storage dam. At the same time, favorable micro-landforms should be fully used to deposit sediments in runoff and floods. Sedimentation ponds should be built in a rectangle shape. The volume is determined by both the amount of sediment in the runoff and the requirements for sediment accumulation. Normally, the optimum size of the sedimentation pond should be 0.6–0.8 m deep with a length-width ratio of 2:1. A rectangle-shaped sedimentation pond that is 2–3 m long, 1–2 m wide, 1.0 m deep and with a pond bottom 0.8 m lower than the intake can accumulate 3 m^3 of silt-sand sediments.

(ii) Fences to block wastes

No matter which sedimentation pond is used, fences should be installed in front of the pond intake. These fences block large debris and litter carried in runoff and floods. The structure of the fence is simple and can be made of iron wires or a metal plate drilled with holes. In less-developed regions, the fence can be made of bamboo strips, wood or willow branches and wickerwork.

9.4.5.4 Water storage system

Frequently used water storage facilities include water storing ponds, water cellars, water-retention wells and dams. Due to differences in landscape, topographic condition, economic potential, construction technique and local building materials, water storage systems differ in shape, pattern and structure. However, the water cellar is the most popular water storage facility in drylands of China.

(i) Types and structure of water cellars

The water cellar is a facility frequently used for storing runoff and rainwater and is a key type of rainwater storage system. Water cellars can be classified according to their shape. They can be cylinder-shaped, ball-shaped and bottle-shaped. They can also be divided according to the anti-infiltration materials use such as red-clay, concrete and cement.

The selection of water cellar types should be based on local topography, soil texture, surface treatment methods and purpose of water use. Table 9.7 shows the types of water cellars used in regions with different soil textures.

Table 9.7 Types of water cellars in regions with different soil texture

Soil condition	Types of water cellar	Volume of water cellar (m^3)
Red soil or loess soil with dense texture	Traditional water cellar	30–40
	Improved cemented water cellar	40–50
	Water pit	60–80
Loam soil with medium texture	Cemented bowl-shaped water cellar	50–60
	Concrete water cellar	50–60
Sandy soil with loose texture	Unsuitable for water cellar; suitable for water storage pond	100

At present, the following water cellars are widely used because of their ease of construction, simple structure and reliable designs.

Concrete ball-shaped water cellar: This type of water cellar is characterized by a simple structure, safety and reliability, longevity, even force distribution, similar internal and external pressures and convenient management. It is suitable for various topographic conditions and soil types. However, it requires high quality building materials and accurate construction techniques.

Concrete cylinder-shaped water cellar: This type of water cellar has a simple structure and long durability and is easy to implement and convenient to maintain. It is suitable for regions with dense soil texture. A reinforcing steel bar should be used at the connection between the cellar wall and the cellar bottom to improve structural strength and to avoid collapse.

Red-clay water cellar: This is a bottle-shaped, traditional water cellar that is popular in rural areas. It is made of and compacted with red clay. Usually, the cellar wall is 8–10 cm thick, and the bottom is 30 cm thick. This cellar is inexpensive and durable. It is characterized by low infiltration and leakage and good stored water quality. However, the construction process is complex and labor intensive. It is suitable for regions with loess and red soil with good soil texture. It is widely used for storing water for people and domestic animals.

(ii) Determining volume of water cellars

In addition to sound technical and economic principles, water harvesting projects must also determine the proper water volume. This is an important element in the development of a water harvesting project. The main factors limiting the volume of a water cellar include topography, landscape and soil texture. In regions with red clay and loess soil, the volume of the water cellar can be large, but in regions with sandy soil and fine loess soil, the volume must be smaller to prevent collapse of the water cellar under pressure.

Generally speaking, the volume of a concrete, ball-shaped water cellar should be limited to 20–40 m^3. The volume of a cylinder-shaped water cellar with a thin concrete wall should be limited to 40–60 m^3. The volume of a red clay water cellar should be limited to 15–50 m^3.

(iii) Layout of water cellars

The layout of water cellars in northwestern China are briefly introduced as follows.

i) Loess ridge and tableland areas

Topographic features: Undulating ridges and tablelands are often found. The land surface is level and covered with dense vegetation. Ridges and tablelands are terraced crop fields or natural rangelands where fewer erosive gullies have been formed.

Layout of the water cellar: Most ridge-top or tableland areas are rural roads or traffic lines, and asphalt-covered or compacted earth road surfaces are optimal locations to harvest runoff or collect rainwater. The location of a water cellar should be installed along the two sides of the road according to local topography or landscape. Experiences in Fengchuan Village of Haiyuan County in Ningxia provide good examples of harvesting runoff. Water-collecting and runoff-harvesting ditches and pools have been installed along the two sides of the highway on a mountain ridge of the village. Rainwater and runoff are collected and transported and stored in the water cellars constructed at the middle of the mountain slope. After a few weeks, the stored water is drawn to irrigate crop fields at the foothill using gravity irrigation.

ii) Hill-front trenched area

Topographic features: Many gullies are distributed in steep hills and converge at the outlet of small watersheds. Converged water spreads toward the outlet forms trenched geomorphology. Roads are built or formed along the trench, and the areas at the two sides of the trench are mostly crop fields.

Layout of water cellars: The water cellars are often installed along the two sides of the road or trench, and water-channeling ditches or canals should be built to lead rainwater or runoff to the water cellars sector-by-sector. Meanwhile, sedimentation facilities should be built in front of the water cellars due to heavy soil erosion and high sediment concentration within runoff. When the water cellar is filled with runoff or rainwater, the cellar intake should be immediately closed. A runoff-harvesting and irrigation pilot project in Nihao Village of Qiying Township of Guyuan County in Ningxia has been successful in constructing runoff harvesting and water cellar irrigation practices in hill-front trenched areas.

iii) Gentle slope area

Topographic features: Foothill terraces, tablelands and trench terraces with gentle slopes and flat landscapes. The loess hilly areas are mostly dissected by gullies, and denudation is severe with wide and deep gullies. Gentle slopes are mainly used for crop cultivation and intercropping of crops and forage (agroforestry practices).

Layout of water cellars: In this area, runoff is produced after soil is saturated. Paths in crop fields are the main sites for harvesting runoff. Water cellars should be installed along the two sides of the field paths. The number of water cellars, or water cellar distribution density, should be determined by the runoff volume from field paths.

iv) Water cellars along roads

In most rural areas of China, different grades of road or highway (such as a province-highway, prefecture-road and county-road) pass through different landscapes and topographic features such as ridges, floodplains, slopes and plains. The changing topographic features should be fully considered during design and installation of water cellars. The site of the water cellar is usually set in a crop field along the road, while water-drawing canals and sedimentation ponds should be well connected to the water cellars.

v) Water cellars near yards

In rural areas, households are widely separated, and houses are mostly one-story buildings surrounded by threshing ground, vegetable gardens and cropland. The yard, threshing ground and house roof can all be used as runoff harvesting sites. Such small-scale runoff-harvesting sites not only meet the needs of domestic water consumption and the growth of the yard plants, but also meet cropland irrigation needs through the installation of a water cellar outside the yard. The 121 project that was popularized in Gansu Province is the best and most successful practice for harvesting runoff in yards (Gao et al., 2005).

References

Ci L J (ED.). 2002. Practical techniques of sand controlling and combating. Beijing: China Forestry Publishing House.

Ding G D. 2007. Sand control techniques. Beijing: China Agricultural Science and Technology Press.

Ding S Y. 2007. Development on water-harvesting and water-saving agriculture in middle and western regions of China. Kaifeng: Henan University Publishing House.

Gao Q Z, Li X Y, Zu R P. 2005. Water provision, collection and conservation in arid area. Beijing: Chemical Industry Press.

Li X Y, Liu L Y, Gao S Y, et al. 2005. Microcatchment water harvesting for growing Tamarix ramosissima in the semiarid loess region of China. Forest Ecology and Management, 214: 111-117.

Wang Z Q. 2000. Sand control along highways in China. Shenyang: Liaoning University Press.

Wu P T. 2002. Rainwater harvesting and utilization. Zhengzhou: Huanghe Water Conservancy Press.

Wu P T, Feng H. 2009. Rainwater utilization in China. Zhengzhou: Huanghe Water Conservancy Press.