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Internal Erosion Due to Water Flow Through Earth Dams and Earth Structures

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1. Introduction

This chapter describes the earth erosion caused by the water flow and seepage that occurs through earth dams, earth embankments and some other structures constructed with earth, such as canal systems, dikes, reservoirs and levees. The erosion in levees on river banks and in levees constructed to protect urban areas exposed to flooding is also discussed. It first describes the mechanism of the soil erosion and the importance of such phenomenon, particularly the damages and consequences that such erosion might produce when it becomes out of control. For instance, one of the main causes of earth dam failures all over the world is the so called piping event, which occurs due to the constant migration of soil particles towards free exits or into coarse openings; this event might occur through the earth embankment or its foundation soil. Another cause of constant earth structure failures is due to uncontrolled saturation and seepage forces. In this context, phenomena known as rapid filling and rapid drawdown, which occur in earth structures subjected to sudden changes of water level (increments or decrements) that modify flow conditions inside a soil mass are assessed. Examples of both failures are given in this chapter.

Each one of the main factors that affect the occurrence of the earth erosion phenomenon is described with detail. Among these factors are: a) the erodibility of the soil; b) the water velocity inside the soil mass; c) geometry of the earth structure. Other important factors discussed here are the homogeneity or anisotropy of the earth structure and its foundation soil, the soil graduation and degree of compaction of the materials used during the construction process; the hydraulic conductivity of such materials, the upstream water energy head, as well as the hydraulic gradient. The importance and the way that each of these factors affect the earth erosion are presented. The calculation of the seepage forces and their effects in slope stability are also described.

The main graphical and numerical methods used for the analysis of the erosion problem considering steady-state and transient flow conditions are discussed. The advantages and shortcomings of each one are emphasized.

Description of the existing procedures for preventing damages due to soil erosion is given in this chapter. Some remediation methods for solving hydraulic problems related to piping or internal erosion, such as impermeable flexible walls, impermeable blankets, grouting

procedures and drainage blankets are also presented. A short section with some recommendations to protect river banks from the erosive attack of water (such as rockfill, *bolsacreto* or *colchacreto* system –concrete bags–, breakwaters, sheet pile walls, etc.) is also included. The construction of graduation filters to prevent piping and movement of erodible soils is also presented. Special emphasis is given in the actual filter design criterion that is recommended by the US Army Corps of Engineers (2000), U.S. Bureau of Reclamation (2000) and the U.S. Soil Conservation Service (1994). Together with these recommendations, those given for earth dams design by A. Casagrande (1968) for avoiding piping and internal erosion in earth dams are given.
Several devices that have been developed to assess how resistant earth materials are to water flow are presented. Additionally, the main recommended laboratory and field tests to analyze soil dispersion or erosion are discussed. A description of laboratory tests to verify the best suitable material to use as a filter and protect a dam core against piping or internal erosion is also given.
Two practical examples related to drainage failures caused by piping and by uncontrolled saturation and seepage forces are presented to illustrate the content of this chapter. In particular, analyses to assess how transient flow caused by rapid filling and drawdown affects soil erosion in typical levees constructed to protect urban areas exposed to flooding are performed by numerical modeling based on finite element method (FEM).
Finally, several recommendations for preventing or solving problems related to soil erosion are presented, together with the main conclusions of this chapter.

2. Soil erosion mechanism in earth structures

Erosion in earth structures due to water flow occurs when the erosion resistant forces are less than the seepage forces that tend to produce it, in such a way that the soil particles are removed and carried with the water flow. The resistant forces depend on the cohesion, the interlocking effect, the weight of the soil particles and the kind of protection they have downstream, if any. Since the seepage through an earth structure is not uniform, the erosion phenomenon increases where there exists a concentration of seepage and water velocity; in places where this concentration emerges at the downstream side, the erosive forces on the soil particles might become very significant. This accentuates the subsequent concentration of seepage and erosive forces there.
This erosion process might occur at any crack that exists in the earth structure, due to differential settlements, seismic movements, tension stresses, or holes caused by dry roots or gnawing animals (rabbits, rats, etcetera). The existence of cracks is also due to shrinkage drying or swelling due to saturation. Favorable internal erosion conditions also exist in contacts between soils and rigid walls, concrete structures, interface with bedrock foundation, etcetera. Areas where ark effect is present are also very susceptible to internal erosion. In all the previous cases, if the vertical effective stresses are reduced by the effect of the water flow, then the existing crack might propagate in such a way that it will create the hydraulic fracture phenomenon.
The erosion starts at any point where the seepage water discharges and works toward the reservoir, gradually enlarging the seepage channel. Depending of the stage of this process, the occurred damage might be classified as a simple “incident”, an accident, or a complete failure.

The first engineers that analyzed this problem were Blight (1910) and Lane (1935), as cited in Casagrande (1968), who defined the susceptibility to soil erosion through a percolation factor *C*, in terms of the horizontal and vertical paths of the water flow, the type of soil and the water head between the upstream and downstream water levels of a hydraulic structure. Figure 1 illustrates the definition of the percolation factor and Table 1 gives the minimum values of *C* recommended by these engineers to avoid soil erosion. Unfortunately, this criterion did not work well for all cases and its use is not recommended (Flores-Berrones, 2000).

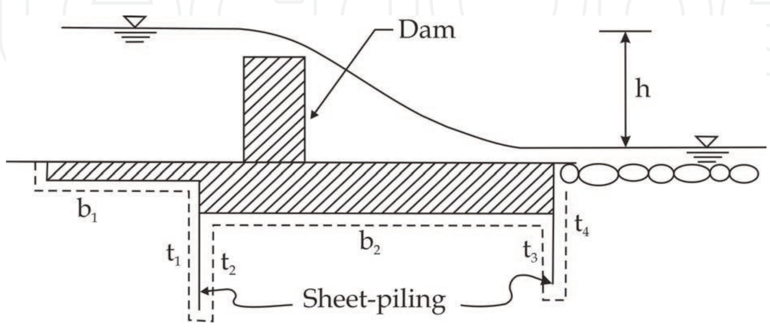


Fig. 1. Dam example given by Blight (1910) to define the percolation factor C_B (Casagrande, 1968)

Material	$C_B = \frac{\sum b + \sum t}{h}$ (Blight criteria)	$C_L = \frac{\sum t + \frac{1}{3}\sum b}{h}$ (Lane criteria)
Fine sand and silt	18	8.5
Coarse sand	12	6.0
Gravel and sand	9	3.0
Boulders, gravel and sand	4	2.5

Table 1. Minimum values of percolation factors to avoid piping, according to Blight and Lane criteria (Casagrande, 1968)

In 1967 Sherard et al. published a table which gives a rough empirical relationship between piping resistance in earth dam embankments and soil types. Such table indicates that soils with the greatest piping resistance are the well compacted high plasticity clays, the intermediate are the well graded coarse sand and sand gravel mixtures, and the least piping resistance are the uniform fine cohesionless sands.

The soil erosion in earth structures, particularly in earth dams and levees, might occur through the embankment, the foundation or from the embankment to foundation (Figs. 2a, 2b and 2c). This kind of erosion has the following phases: a) initiation and continuation of erosion, b) progression to form a pipe, and c) formation of a breach (Fell et al., 2003). The initiation of the soil erosion usually starts at the exit point of the seepage, and retrogressive erosion results in the formation of a "*pipe*". In fact, this is the reason why this erosion phenomenon is also called *piping* (see Fig. 2c). The removal of a small portion of the earth embankment or foundation by erosive action at any point, particularly at the exit part of the downstream slope, accentuates the subsequent concentration of seepage and erosive forces in that zone.

This effect, due to concentrated water leaks, varies somehow from what is called *suffusion* or internal instability, which implies the internal movement of soil particles due to the adjustment of internally unstable soils; this is the case of gap graded or very broadly graded soils, such as coarse sands and gravels with small quantities of fine soils.

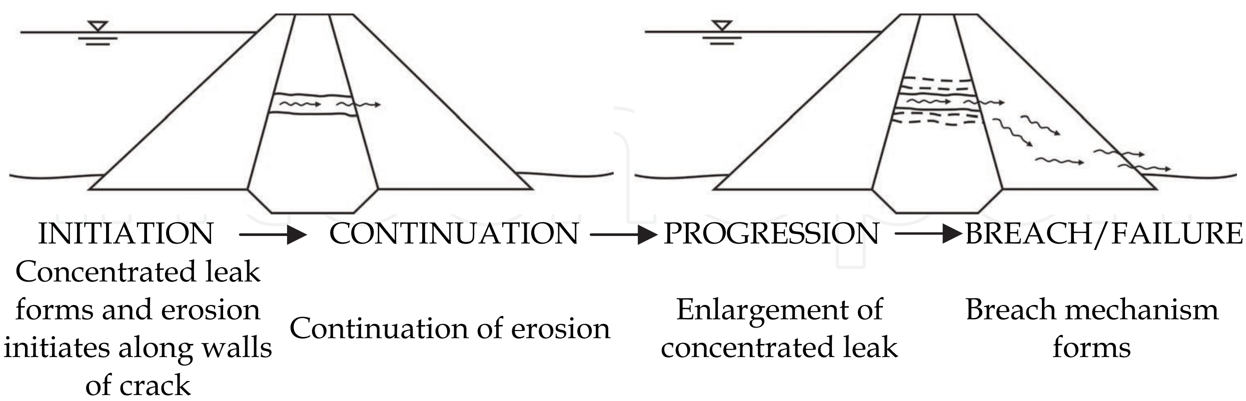


Fig. 2a. Piping in the embankment initiated by concentrated leak (After Fell et al., 2003)

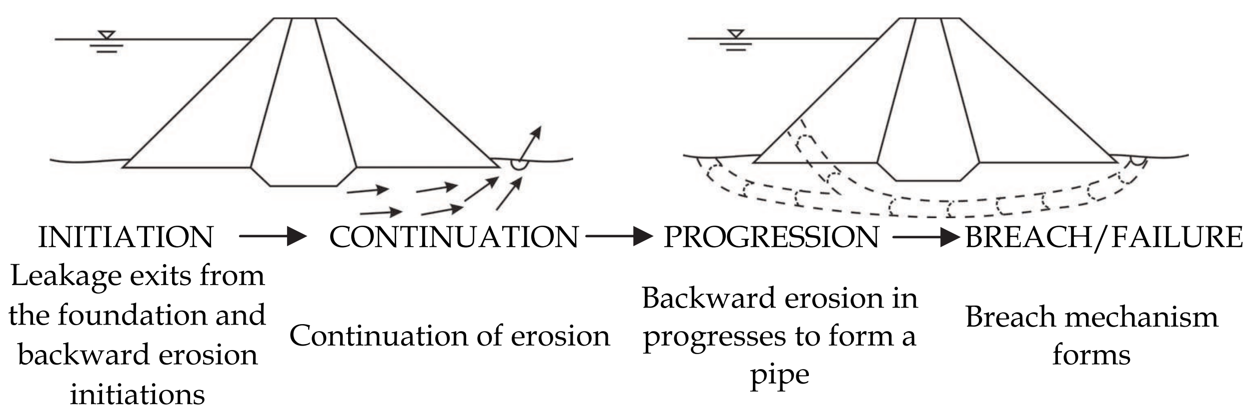


Fig. 2b. Piping in the foundation initiated by backward erosion (After Fell et al., 2003)

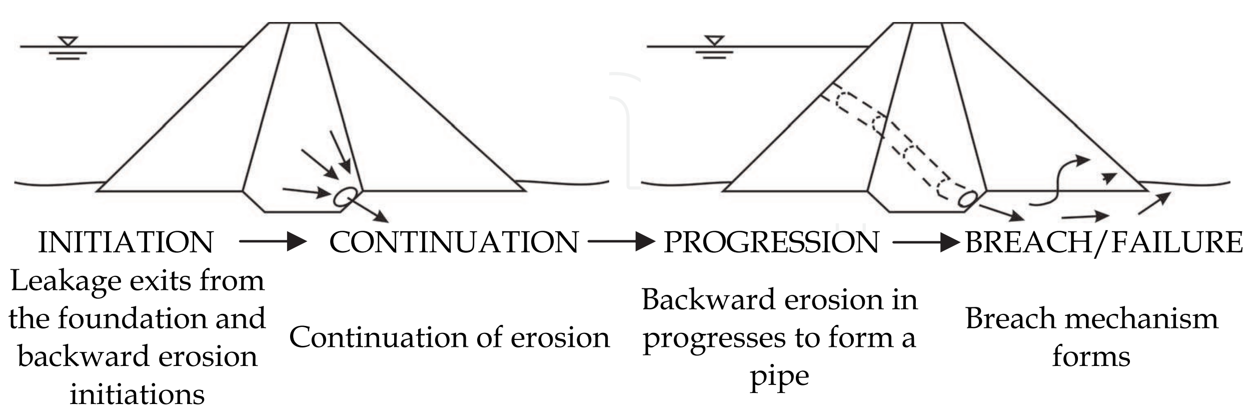


Fig. 2c. Piping from embankment to foundation initiated by backward erosion (After Fell et al., 2003)

The soil erosion problems also might occur in river banks. In tropical regions the intense rainfalls originate large and quick variations of the water surface of rivers. Problems related to rapid filling and drawdown conditions due to these oscillations of river water level and also to the seepage forces generated by rain infiltration at the crown of the levees protecting the margins of rivers are observed. Instability problems in river banks commonly begin with erosion, which in some parts (depending on the type of soil) causes *piping* and might result in landslides as shown in Figure 3 (Auvinet & Lopez-Acosta, 2010).

Fig. 3. Evidences of instability in river banks caused by erosion (Auvinet & Lopez-Acosta, 2010)

3. Factors affecting the earth erosion phenomenon

Main factors affecting the erosion phenomenon are: a) the erodibility of the soil; b) the water velocity inside the soil mass or the water velocity on a river; c) geometry of the earth structure through its size and shape.

Erodibility can be defined as the relationship between the velocity of the water flowing over the soil and the corresponding erosion rate experienced by the soil. This definition of erodibility presents some problems because water velocity is a vector quantity which varies everywhere in the flow and is theoretically zero at the soil-water interface. It is preferable to quantify the action of the water on soil by using the shear stress applied by the water on the soil at the water-soil interface. Thus, erodibility of a soil can be defined by the relationship between the erosion rate $\dot{Z}$ and the shear stress τ at the soil-water interface (Briaud, 2008):

$$\dot{Z} = f(\tau) \quad (1)$$

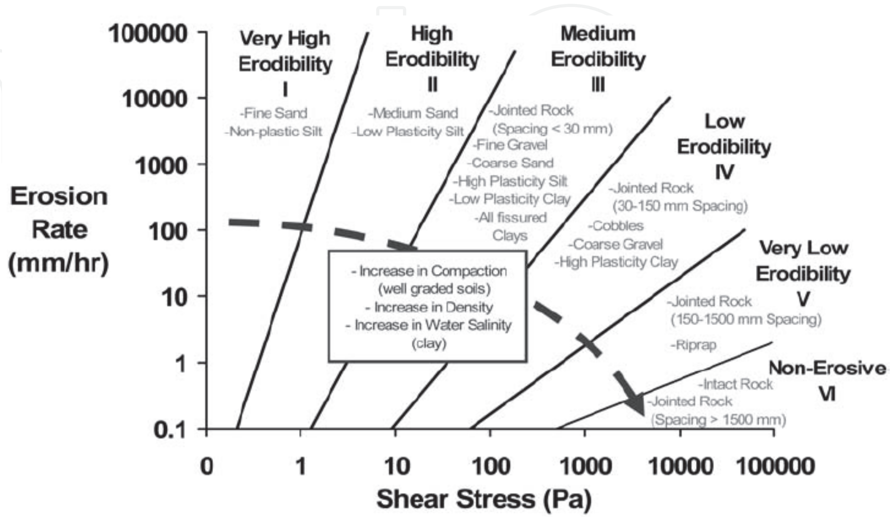


Fig. 4. Proposed erosion categories for soils and rocks based on shear stress (Briaud, 2008)

As explained later in section 7.1, this erosion function can be obtained by using a laboratory device called the erosion function apparatus –EFA– (Briaud et al., 2001). Recently, based on erosion testing experience, *erosion categories* have been proposed in terms of water velocity or shear stress. Erodibility as a function of water velocity is less representative and leads to more uncertainties than using shear stress, as mentioned above. Then, Figure 4 shows these proposed erosion categories for soils and rocks based on shear stress (Briaud, 2008). According to this figure, it seems that grain size controls coarse grained soil erosion and plasticity seems to have a significant influence on fine grain soil erosion.
Additionally, some of the most important properties influencing erodibility of soils are listed in Table 2.

Soil water content	Soil dispersion ratio
Soil unit weight	Soil cation exchange cap
Soil plasticity index	Soil sodium absorption rat
Soil undrained shear stress	Soil pH
Soil void ratio	Soil temperature
Soil swell	Water temperature
Soil mean grain size	Water salinity
Soil percent passing #200	Water pH
Soil clay minerals	

Table 2. Soil properties influencing erodibility (Briaud, 2008)

On the other hand, the velocity of the water flow through the soil mass depends on the hydraulic conductivity of the soil and the hydraulic gradient. According to several experimental tests, the water flow through fine soils is considered to be *laminar* (water particles move parallel each other), and such flow follows the Darcy's law, giving the following expression:

$$V = ki \tag{2}$$

Where V = discharge velocity, k = hydraulic conductivity and i = hydraulic gradient.
The hydraulic conductivity of the soil is determined through laboratory or field tests; for clean sands and gravel mixtures the hydraulic conductivity varies from 10^{-1} to 10^{-3} cm/sec, whereas for very fine sands to homogeneous clays the k value varies from 10^{-4} to 10^{-9} cm/sec (Lambe, 1951). The hydraulic gradient is given by the difference of the water head h_1 at the entrance and the water head h_2 at the exit of a soil section, where there exist a water flow, divided by the length L of the flow path. Using the information provided by Figure 5, the hydraulic gradient is given by the following expression:

$$i = (h_1 - h_2)/L = \Delta h/L \tag{3}$$

As it can be observed in Eq. (3), the hydraulic gradient is dimensionless. Later in this chapter, we demonstrate the existence of a hydraulic gradient that makes the effective stresses among soil particles become zero, in such a way that the friction resistance forces against erosion become nullified. The smallest hydraulic gradient that nullifies such stresses is called *critical* and its value usually ranges between 1 ±0.20.
Some other factors affecting the internal soil erosion or piping in soils are: a) the degree of compaction of the soil layers on the earth structure; b) the homogeneity and quality control

on the construction of the earth structure; for instance, if the permeability of the soil layers varies from one another, there might exist a mayor seepage concentration on those layers of higher permeability; c) the type of preventive measures in the downstream side of an earth structure, such as graded filters designed to prevent displacement of the fine particles; d) the compaction control along the installation of pipeline conduits; along such installations, many initial leaks and piping effects have been reported in the literature (Flores-Berrones et al., 2011); e) existence of hydraulic fracture in certain zones of an earth structure, where the water pore pressure becomes larger than the minor principal stresses (Peck, 1976); f) as it was already mentioned, the high plasticity soils, such as clays of high plasticity, are less vulnerable to erosion than cohesionless soils.

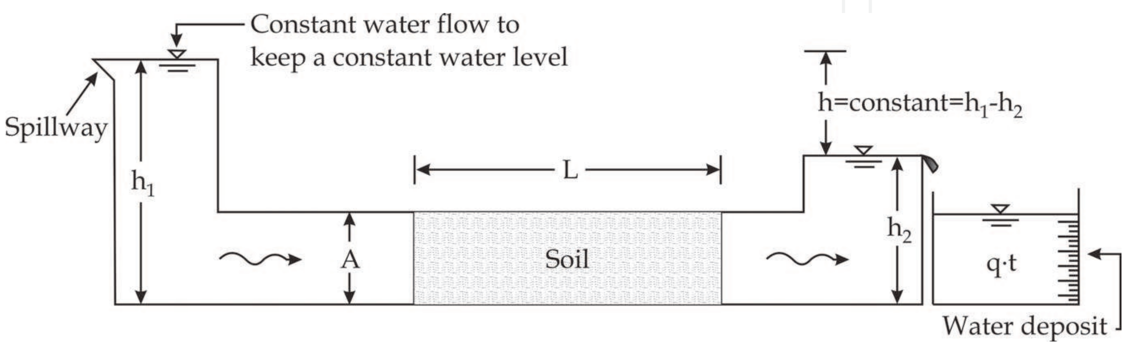


Fig. 5. Constant water head permeameter

4. Analysis of seepage forces and their effect in slope stability

There are several practical cases where it is necessary to consider the forces produced by the water flow for the slope stability analysis of an earth structure. In the case of earth dams and levees, the water flow conditions that might occur and have to be consider for slope stability analysis are the following: a) transient flow that occurs during the first filling or a rapid drawdown conditions; b) constant flow which occurs sometimes after the reservoir is operating under regular water flow conditions; c) anisotropic water flow when the horizontal permeability is different than the vertical one. These three conditions might be more complicated when seismic forces have to be considered.

The water flow effects on the stability of an earth structure are the following: a) internal soil erosion o piping by removing and transporting soil particles, starting a duct that might increase rapidly, producing a complete failure; b) water pressure increase that will decrease the effective stresses and therefore decrease in the shear strength of the soil; c) increment on the water flow forces due to gravity might significantly decrease the safety factor and produce a slope failure.

Using either the graphical or numerical analysis, as it is explained later in this chapter, it is possible to obtain the hydraulic gradient at any point of the flow region.

For the most common practical cases that exist in earth dams and levees, Flores Berrones et al. (2003) have demonstrated that the water flow analysis can be reduced to a two dimensional system, so equation (4) is the one that must be considered for steady-state conditions:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \qquad (4)$$

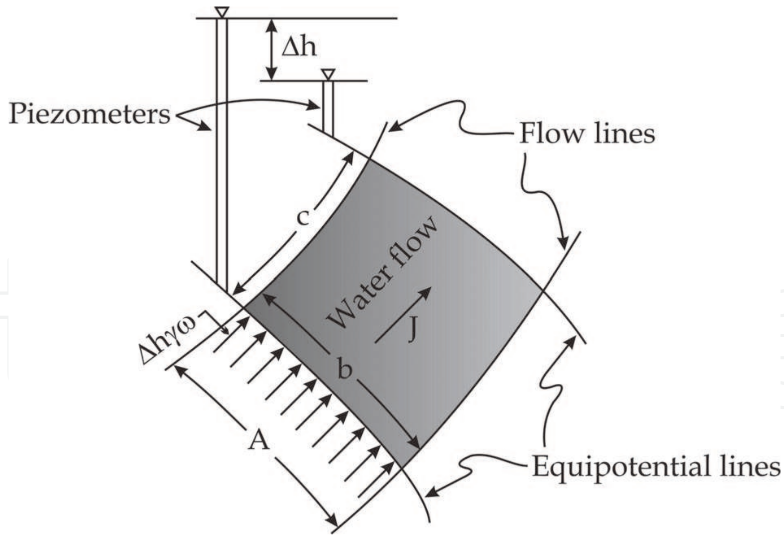


Fig. 6. Water flow forces over a soil element from the flow net (Flores et al., 2003)

This expression is the so-called Laplace's equation, which can be solved by different methods. The most common technique is the graphical solution to such equation, which is represented by two families of curves that intersect at right angles to form a pattern of square figures known as a *flow net*. In hydromechanics one set of these lines is called the *streamlines* or *flow lines*, and the other *equipotentials*. The flow net is constructed by setting first the boundary flow and equipotential conditions, and later on some additional flow lines are drawn in such a way that there will be, between each pair of flow lines, the same amount of water volume Δq. The equipotential lines are constructed in such a way that there exist equal head losses, Δh, between adjacent equipotential lines. Most flow nets are composed of curves that form curvilinear squares. A detail description to construct a flow net for any particular problem is given by Cedergren (1989) and Flores-Berrones (2000). From a flow net it is possible to obtain the total volume of water per unit of length at any part of the flow region, and also the water pressure, hydraulic gradient and flow velocity at any point of the studied domain.

On the other hand, the force over a soil element of a flow net, produced by a water flow, is analyzed in Figure 6. It can be observed in such figure that the force J per unit of length over the soil element is given by:

$$J = \Delta h \, \gamma_w A \, (1) = \Delta h \gamma_w A \tag{5}$$

Where A is the cross-sectional area of the soil element, and γ_w is the volumetric unit weight of water. The seepage force per unit of volume is:

$$j = \frac{\Delta h \gamma_w A}{cA} = \frac{\Delta h}{c} \gamma_w = i \gamma_w \tag{6}$$

Where i is the hydraulic gradient.

For regions in which there exists a uniform water flow, with a constant hydraulic gradient, the seepage force is given by:

$$J = i \, \gamma_w \, V \tag{7}$$

Where V is the soil volume through which the water flow is taking place. If the hydraulic gradient is not constant but is a point function, the seepage force is the vector sum of all the forces applied in the volume of each element; for this case such seepage force is given by:

$$J = \int_V i dV \tag{8}$$

To illustrate the effect of the seepage force on soil erosion and slope stability, in Figure 7a are given the total, neutral and effective stress distribution of a saturated soil sample, where there is not a flow, whereas Figure 7b shows those stresses under the existence of an upward water flow. In the last figure (Fig. 7b), it can be observed the decrease of the effective stresses as a function of the water head h. It is important to notice that such stresses are nullified when:

$$h = D\gamma_m' / \gamma_w \tag{9}$$

Where γ_m' is the submerged weight of soil, and γ_w is the unit weight of water. Since for most soils $\gamma_m' \approx \gamma_w$, the effective stresses become null when $h/D = 1$. As it was mentioned before, this case is known as critical hydraulic gradient, and when it takes place, the resistance friction forces of the soil particles against erosion also become zero. Under such conditions, the probability of soil erosion, particularly for fine cohesionless soils, is very high.

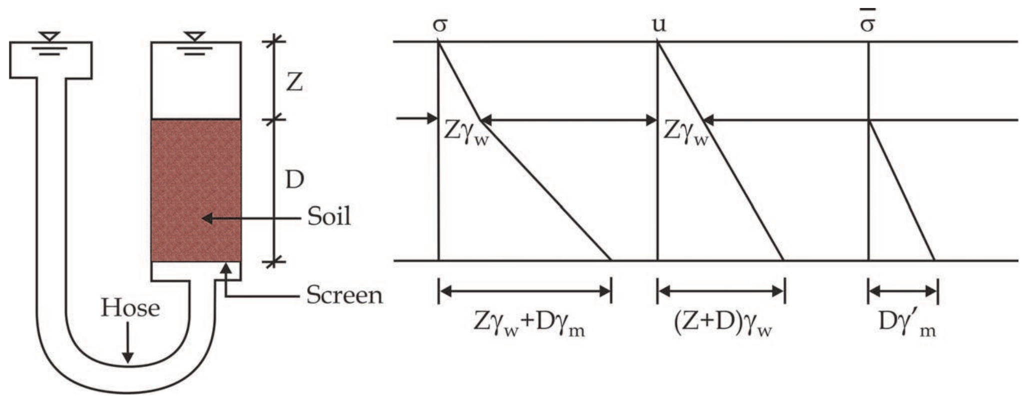


Fig. 7a. Total (σ), neutral (u) and effective ($\bar{\sigma}$) stress distribution in a soil sample without any water flow (Flores et al., 2003)

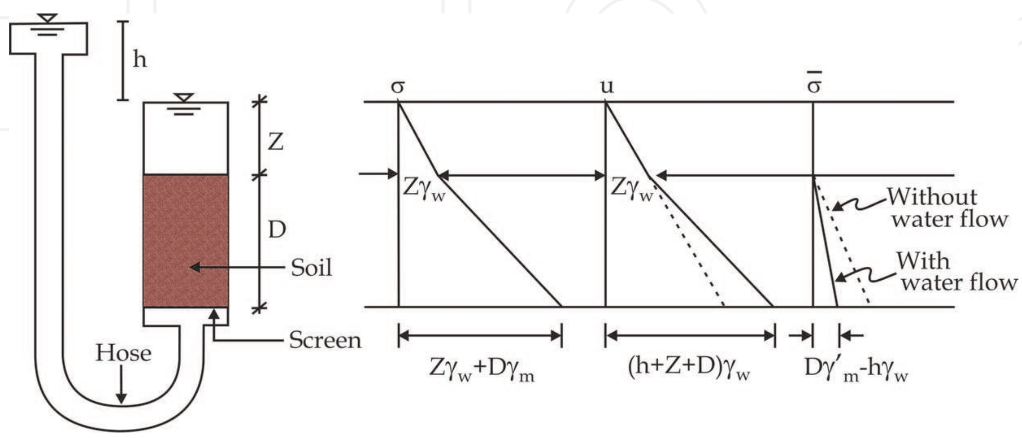


Fig. 7b. Total (σ), neutral (u), and effective ($\bar{\sigma}$) stress distribution in a soil sample with an upward water flow (Flores et al., 2003)

As it has been demonstrated by some authors (Cedergren, 1989; Flores-Berrones et al., 2003), seepage forces might decrease (or increase in some particular cases) the factor of safety on the stability of earth dams and levees.

5. Graphical and numerical methods for analyzing the erosion problem

Solving soil erosion problems involves the calculation of hydraulic gradients, seepage forces, water or pore pressure, flow velocities, flow rates, among other variables. The assessment of such properties is carried out by solving partial differential equations. For steady-state conditions, water flow is calculated by Laplace's equation (see eq. 4, applicable to homogeneous and isotropic soils). For transient flow conditions in a homogeneous and isotropic soil domain the following partial differential equation is used:

$$div\left[kgrad\left(h\right)\right]+c\frac{\partial h}{\partial t}=Q \qquad (10)$$

Where k is hydraulic conductivity of soil, h is hydraulic potential (also named hydraulic head), c is specific capacity of soil, t is elapsed time and Q is a discharge quantity corresponding to a possible source within the medium.

The above equations (eqs. 4 and 11) combine Darcy's law and continuity of flow. They can easily be generalized to the case of heterogeneous and anisotropic soils (Auvinet & Lopez-Acosta, 2010; Lam et al., 1987). In the case of partially saturated soils, specific capacity depends on porosity and degree of saturation. Deformability of soil skeleton is commonly ignored. At the same time, degree of saturation and permeability depend on local pressure (Van Genuchten, 1980).

The resolution of the above equations can be performed in an exact or an approximate form, by analytical or numerical techniques (Alberro, 2006; Cedergren, 1989; Lopez-Acosta et al., 2010; among others). Thus, the methods that can be used for evaluating steady and transient state flow conditions include:

- Analytical solution of partial differential equations (Alberro, 2006).
- Approximate graphical method simply named *flow nets* for steady conditions, or *transient flow nets* for transient conditions (Cedergren, 1989; Flores-Berrones, 2000).
- Numerical techniques such as *finite element method* (e.g. *Plaxflow*, Delft University of Technology, 2007), or *finite differences* (e.g. *Flac3D*, ITASCA Consulting Group Inc., 2009).

In general, exact and analytical solutions are laborious when geometric, hydraulic and boundary conditions become complex. Approximate solutions are usually used. Nowadays, numerical methods are preferred with increasing frequency due to their easy adaptation and automation to widely varying conditions, and in general because of their capability for solving complex problems. Numerical methods have been applied by different authors (Auvinet & Lopez-Acosta, 2010; Freeze 1971; Huang & Jia, 2009; Lam & Fredlund 1984; Lam et al., 1987; Ng & Shi, 1998; among others). The present chapter focuses on the finite element method (FEM), using the *Plaxflow* algorithm (Delft University of Technology, 2007), a specialized computer program which is applied to solve steady and transient flow problems by means of the approximate solution of Laplace's equation and equation 11. This algorithm utilizes the previously mentioned Van Genuchten model to represent flow in unsaturated soils and allows carrying out steady-state analyses following the methodology indicated in

Figure 8a; and transient flow analyses in two different ways: 1) *Step-wise conditions* and, 2) *Time-dependent conditions* as illustrated in Figure 8b. The *Plaxflow* algorithm provides hydraulic potential field, flow velocity field, pore pressure, degree of saturation field, among others, as exposed below.

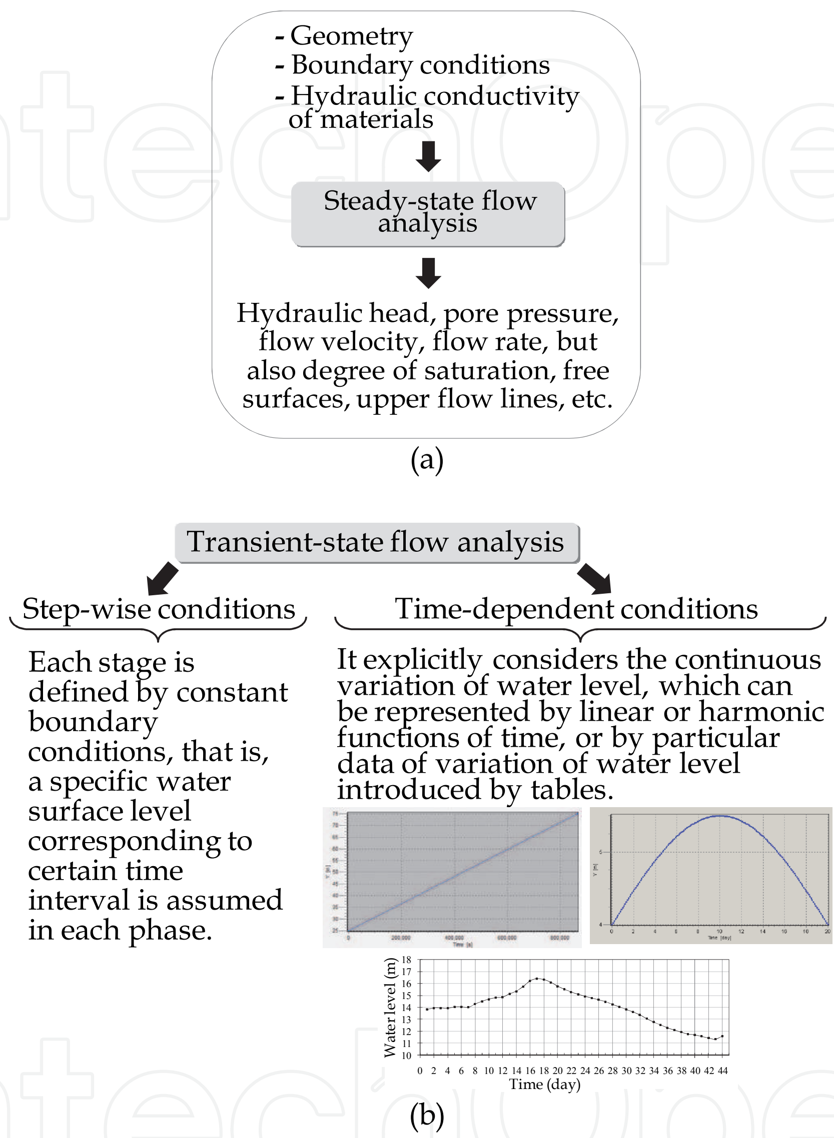


Fig. 8. Types of flow analyses performed with *Plaxflow* algorithm (Lopez-Acosta & Auvinet, 2010)

6. Procedures and practical recommendations for preventing damages due to soil erosion

The design of an earth dam or a levee is based on analytical studies of the site of construction and on personal experience of the individual designer. At a given site, it is possible to design a variety of earth dams which would be both, economical and safe. The final design depends on the quantities, types and location of the soil available for constructing the embankment, as well as the size and shape of the valley and the nature of the foundation. Sherard et al. (1967) present several typical designs of earth and earth-rock dams that have been constructed in the USA. Such dams vary from homogeneous earth dams (constructed on rock or impervious stratum) to dams with embankments constructed with different graduation materials and founded on either impervious or pervious soil stratums.

As it was mentioned before, internal erosion might occur through the embankment or through the dam foundation. To prevent earth erosion through the embankment, several measures might be taken. The following recommendations should be considered:

a. Obtain the best selection of the available construction materials.
b. Control the homogeneity of the materials during the construction process.
c. Use transition zones between the coarse and fine materials.
d. Use properly designed filters and drains for all earth facilities exposed to the damaging actions of water in their foundations or around the impervious core.

Properly designed filters should satisfy the following characteristics:

a. The filter should intercept water flowing through cracks or openings in protected soil and block the movement of eroding soil particles into it. Therefore, there must be a relationship between the size of the particles of the protected soil and the openings of the filter.
b. Filters should have enough permeability to avoid high seepage gradients or water pressures; this hydraulic condition means that the filter should act as a good drain.
c. Filter grain particles should not have migration or suffusion due to the water flow action. This means that the filters should be designed to keep its internal structure always stable.

In relation to the drain design, Cedergren (1989) recommends that "designers should analyze every component of a drainage system (filters, conducting layers, collectors, outlets, and so on) to ensure that the entire system will have the necessary capacity and will function as intended". On the other hand, the criteria for the filter design was first established by Karl Terzaghi (1929) and later on modified by several authors (Sherard & Dunnigan, 1989; Wan et al., 2002) and several institutions (ICOLD, 1994; USACE, 2000; USBR, 2000; US Soil Conservation Service, 1994; among several others). Applications of these criteria to a case history and its implications are reported by Flores-Berrones et al. (2011). Sometimes it is necessary to use multi-layer filter systems, in which the characteristics for each layer should satisfy the selected design criteria for those materials surrounding the one under analysis.

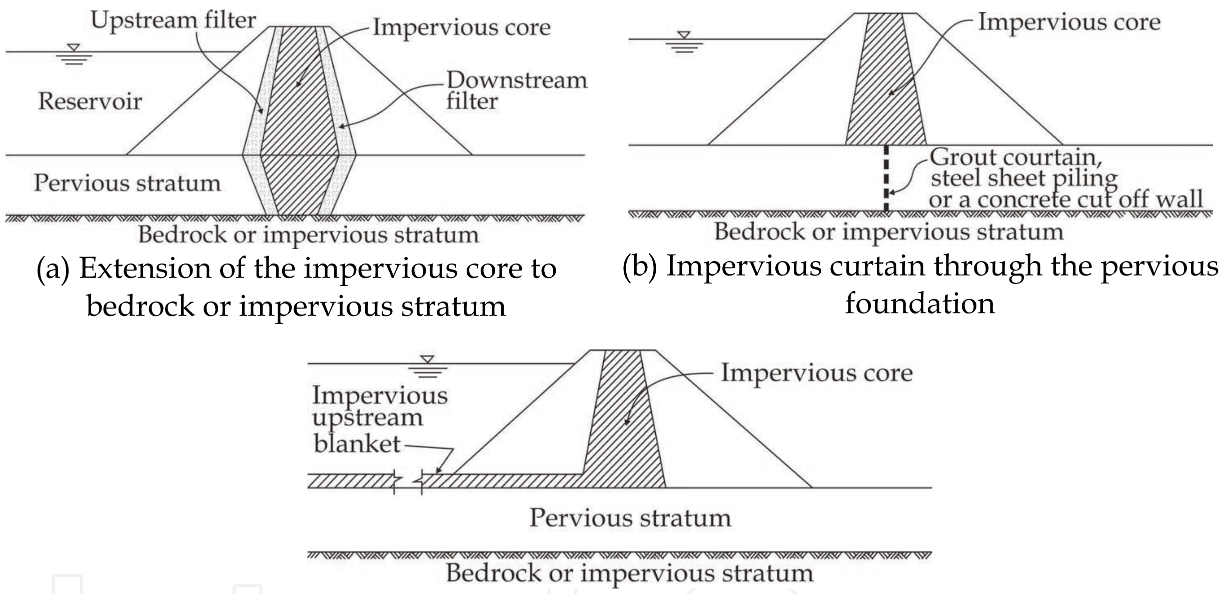
For preventing soil erosion or piping through a pervious foundation of an earth structure, the following measures might be taken:

a. Continuation of the impervious zone of the embankment up to an impervious soil stratum or bedrock (Fig. 9a).
b. Construction of a grout curtain or a steel sheet piling or a concrete cutoff wall, below the impervious core (Fig. 9b).
c. Impervious upstream blanket, in order to decrease the exit hydraulic gradient (Fig. 9c).
d. Combination of recommendations 1), 2) and 3) referred above. Sherard et al. (1967) present several examples of earth and earth-rock dams that have been constructed around the world, in which it is possible to observe alternative design solutions.

Cedergren (1989) recommends the use of high standards for all facets of design and construction, use relatively wide impervious cores and other features that hold seepage quantities and hydraulic gradients to the lowest practical levels, and provide well designed and constructed filters and drains wherever needed. It is also recommended special precaution when designing filters to protect gap-graded soils, and to avoid severe segregation during the construction stage of any filter.

To protect the upstream faces of earth dams, levees, and in any other situations in which erodible soils must be protected from rain currents and wave action, a layer of rock should be placed. One or more filter layers should be placed between the rock slope protection layer and the soil material that forms the earth embankment. Each transition filter layer must also satisfy the filter criteria in such a way that internal erosion or piping effect does not occur. For multi layer filters, the US Corp of Engineers (2000) and the US Bureau of Reclamation (USBR, 2000) recommend that grading curves of such filters should be more or less parallel between each other, in order to avoid segregation or clogging.

When filter fabrics are used, the protective filter is only the thickness of the fabric, which may be as little as 1mm. It is therefore very important that no holes, tears or gaps be allowed to form in the fabric. In this case, the openings between the filaments of a fabric should not be so large that significant loss of soil can occur. If the D_{85} of a soil is larger than the near maximum opening size of the fabric, little soil should be able to move through the mesh of the fabric (Cedergren, 1989).



(a) Extension of the impervious core to bedrock or impervious stratum

(b) Impervious curtain through the pervious foundation

(c) Construction of an impervious upstream blanket

Fig. 9. Measures for preventing soil erosion or piping through a pervious foundation of an earth structure

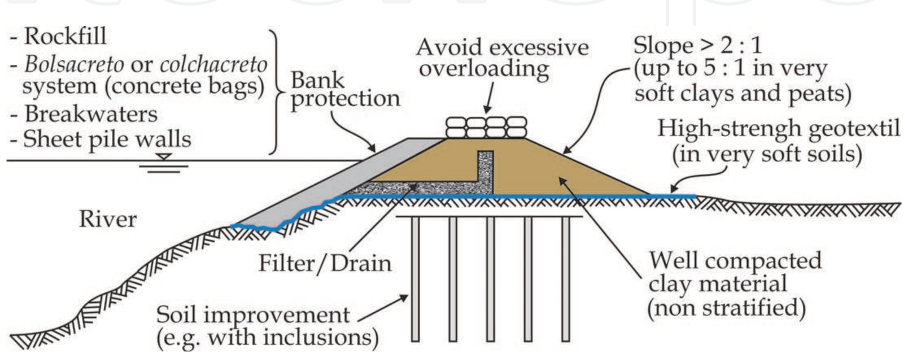


Fig. 10. Recommendations to protect levees on river banks (Auvinet et al., 2008)

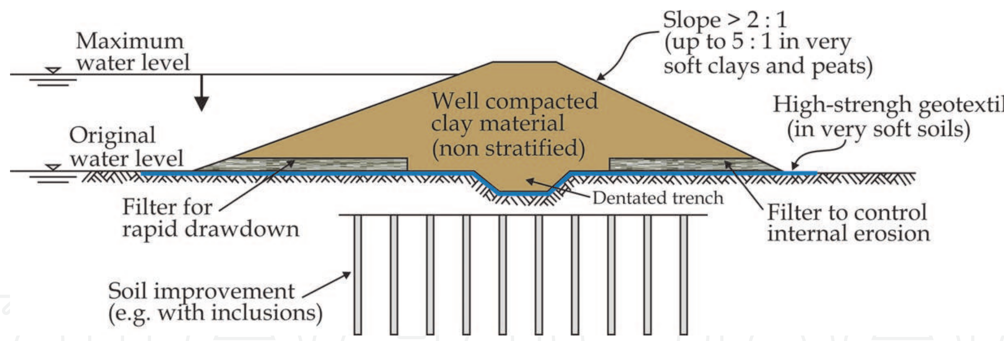


Fig. 11. Recommendations to protect levees in urban areas exposed to flooding (Auvinet et al., 2008)

In addition, Figures 10 and 11 illustrate respectively some practical recommendations that should be taken into account for the protection of levees on the river banks, and levees that are built in order to protect urban areas exposed to flooding (Auvinet et al., 2008).

7. Laboratory and field tests for analyzing erodible and special soils such as dispersive

7.1 Analysis of the soil erodibility

Several devices have been developed to evaluate how resistant earth materials are to water flow. Some of them are the *rotating cylinder* to measure the erosion properties of stiff soils (e.g. Chapuis & Gatien, 1986); the *jet test* to evaluate the erodibility of surface soils (e.g. Hanson 1991), and the *hole erosion test* to measure the erosion properties of stiff soils (e.g. Wan and Fell 2004). Another popular device developed in the early 1990s to measure the erosion function is the called *Erosion Function Apparatus* –EFA– (Briaud et al., 2001). The EFA test (Fig. 12) consists of eroding a soil sample by pushing it out of a thin wall steel tube and recording the erosion rate for a given velocity of the water flowing over it. Several velocities are used and the erosion function is defined through the results of this test (Briaud et al., 2001).

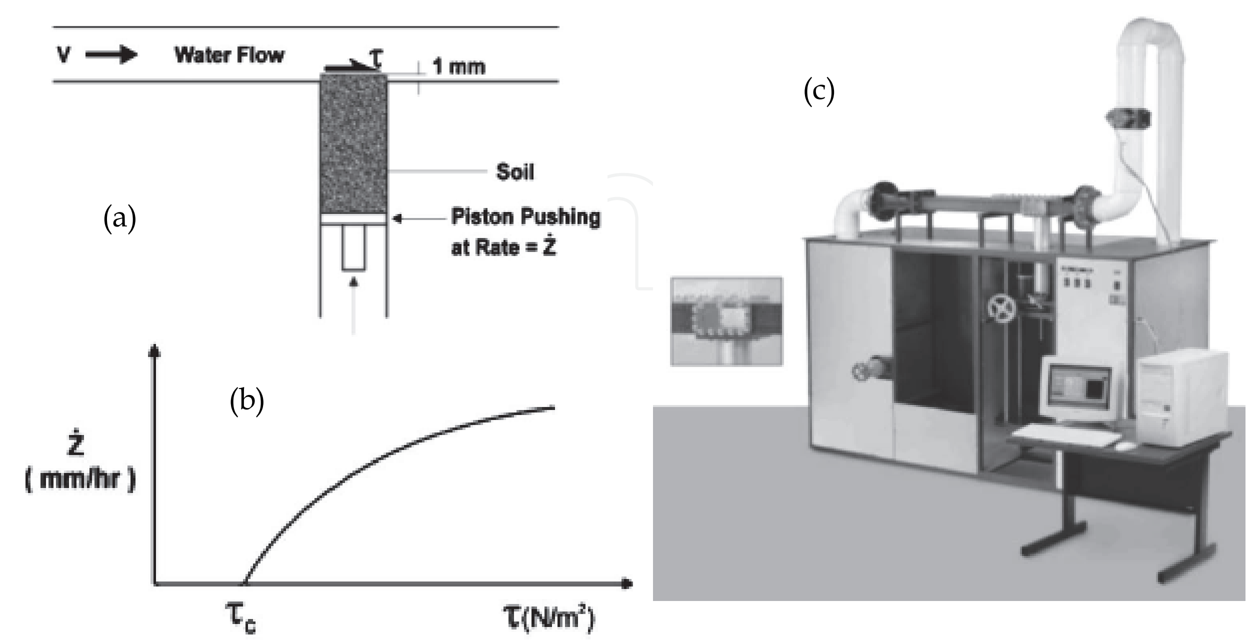


Fig. 12. Erosion Function Apparatus –EFA– (Briaud et al., 2001)

7.2 Identification of dispersive soils

Additionally, as it was mentioned before, soil erosion is likely to occur in certain types of soils. Among those are certain types of clay which erode by a process called dispersion or deflocculation, that occurs when the clay mass is in contact with water. If water is flowing, individual clay particles are detached and carried away through erosion channels or *pipes* that can form rapidly. As it is established by Cedergren (1989), one of the problems related with dispersive clay action, is that the deflocculation process starts as soon as there is a significant flow of water, as it can occur through poorly compacted or cracked layer in an impervious core, or along inadequate bonded contacts with rock foundations, abutments, or outlet conduits extending across the impervious core.

The practical relevance of dispersive clays in dam engineering, started about 60 years ago after realizing that it was the main cause of piping failure of several small earth dams and levees. Most of the earth embankment failures caused by dispersive soils occur during the first filling. If there are no well designed and constructed filters upstream and downstream of the core embankment that has these clays, the probability of an internal erosion failure will be very high. This probability might increase when preexisting surface erosion caused by rainfall contributes to the formation of superficial channels that become connected to tunnels originated by internal erosion. As this type of soil is not possible to identify through the conventional index tests, it was necessary to develop certain laboratory and field procedures for its identification.

Whereas the susceptibility to erosion in cohesionless soils, such as fine sands and silts, is due to high values of water flow velocity, hydraulic gradients and seepage forces, normal clays are usually erosion resistant, except for water velocity higher than 1 m/sec. Nevertheless, for dispersive clays the erosion phenomena occur due to causes that are different to those associated with granular soils. Such causes are due to the following characteristics:

a. **Physic-chemical characteristics.** The erosion resistance property that normal clays have, due to the electrochemical attraction between clay particles, is reduced to a minimum in dispersive clays, due to their physic-chemical characteristics. Therefore, under a low water flow the dispersive clay particles tend to separate and taken away easily by the water current. The rate of erosion of these clay particles might be higher than the one that takes place in fine sands and silts. There are several factors that affect the dispersive action of these clays, among which are their chemistry and mineralogy, as well as the kind of salts that exist in the pore water and the circulated water. The principal difference between dispersive clays and ordinary erosion-resistant clays appear to be the nature of the cations in the pore water of the clay mass. Dispersive clays have a preponderance of sodium, whereas ordinary clays have a preponderance of calcium, potassium, and magnesium cations in the pore water (Knodel, 1988).

b. **Physical characterization.** Dispersive clays are not related to any specific geological origin, but they have been founded under alluvial environment, in lakes and in flood plain deposits. They are very important in hydraulic structures, such as earth dams, levees and channels, since many of them are constructed over such soils. In some cases marine deposits have the same pore water salts as dispersive clays, and the residual soils from such deposits are also dispersive.

c. **Mechanical characterization.** The external erosion or piping, caused by a water flow is very obvious and it occurs in granular or cohesionless soils. As it has been said, in this case it starts at the discharge end of a leak, at the downstream side of an earth embankment, where there exists a high hydraulic gradient; such phenomenon progresses upstream, forming a kind of pipe until it reaches the water source. With dispersive clays, however, the internal erosion is due to a deflocculation process and it might start at the upstream side where there is the water source; the tunnel-shape passage or pipe, that is formed, is propagated toward the downstream side. If such dispersive soils exist in areas where there are already some cracks, or not well compacted zones as those presented along conduits, such cracks might increase and propagate very rapidly causing a dam failure.

7.2.1 Field and laboratory test for dispersive soils

During the field investigation to construct an earth dam, particularly when looking for the materials that might be used to construct the embankments, it is very important to identify the existence of dispersive soils. This identification should be done first through one of the special field tests that exist for this purpose. Although the results of such tests must be verified through laboratory tests, field tests might give a good preliminary evaluation of the dispersivity of the soils under investigation. Knodel (1988) presents a good description of the most common laboratory and field tests that are used in the engineering practice to identify the dispersivity of soils. Among them are the following: a) for field: *crumb test*, *water drop test*, *dissolved sodium test*, and *turbidity test*; b) for laboratory: *crumb test*, *the double hydrometer test*, *pinhole test* and *chemical test*.

7.2.2 Design considerations when constructing with dispersive clays

For any earth construction it is necessary to investigate, by using one or more of those methods mentioned above, the existence of dispersive soils; this investigation can be carried out through soil samples obtained in open wells during the soil exploration phase. Once the construction materials have been identified, a decision to use or refuse them has to be taken.
Sometimes dispersive soils might be used in earth structures if they are mixed with lime or if well designed filters and drains are installed. If for economical reason it is decided to use dispersive clays, the following conditions have to be taken into account:

a. Arching. This problem might occur in zones around conduits through the embankment, near concrete structures, and at the foundation interface. In order to avoid negative effects, special control of compaction and moisture content during construction should be taken.
b. Cracking due to differential settlements caused by soil consolidation, stress concentration, two or three dimensional effects, etcetera, should be avoided.
c. Soil improvement of the dispersive clay, by adding hydrated lime or non dispersive clay of medium to high plasticity. Special care should be taken in compacting soil adjacent to rigid structures such as conduits.
d. Construction control. Special standards and specifications should be used when dispersive soils are involved in the construction of earth structures, particularly those related to soil density and compaction procedures. For instance, there should not be moisture concentration while adding water to obtain the specified water content during layers' compaction. Special monitoring consideration to dams with cores containing dispersive soils, should be giving during the first filling, in order to prevent any piping or internal erosion effect. Observation instruments are particularly recommended to periodically measure water pressures, water leaks and water levels at different zones of the embankment.

8. Practical examples to illustrate the analysis of earth erosion problem caused by rapid filling and drawdown conditions in embankments

8.1 General settings

The wet slope of an earth dam, lake or river banks and channel slopes are frequently subjected to sudden changes of water level (increments or decrements), which modify flow conditions inside the soil mass. Flow velocities, hydraulic gradients and seepage forces might, in extreme conditions, cause soil erosion problems ranging from slight to severe, such as piping or even the total failure of the structure. These phenomena, known as *rapid filling* and *rapid drawdown*, are complex problems in which the magnitude and rate of filling or drawdown, hydraulic conductivity and porosity of materials constituting the earth structure, geometry of slope and initial boundary conditions of flow are involved (Auvinet & Lopez-Acosta, 2010). By using the *Plaxflow* algorithm (Delft University of Technology, 2007), analyses to assess how these two phenomena affect soil erosion in earth structures are carried out through a numerical modeling based on finite element method (FEM) (Auvinet & Lopez-Acosta, 2010; Lopez-Acosta et al., 2010).

8.2 Analysis considering only rapid drawdown phenomenon

In this practical example, the effect of rapid drawdown phenomenon on erosion problems in a typical embankment is analyzed (Auvinet & Lopez-Acosta, 2010). Simplified geometry of the studied domain and boundary conditions considered in this analysis are shown in Figure 13. Rate of drawdown was established at 1.1m/day. Thus, a total dewatering of 5.5m in 5 days was assumed in this analysis. In the same way, it was accepted that embankment is constituted by a homogeneous and isotropic material with hydraulic conductivity k=1×10^{-5} m/s and porosity n = 0.3 (void ratio e = 0.43).

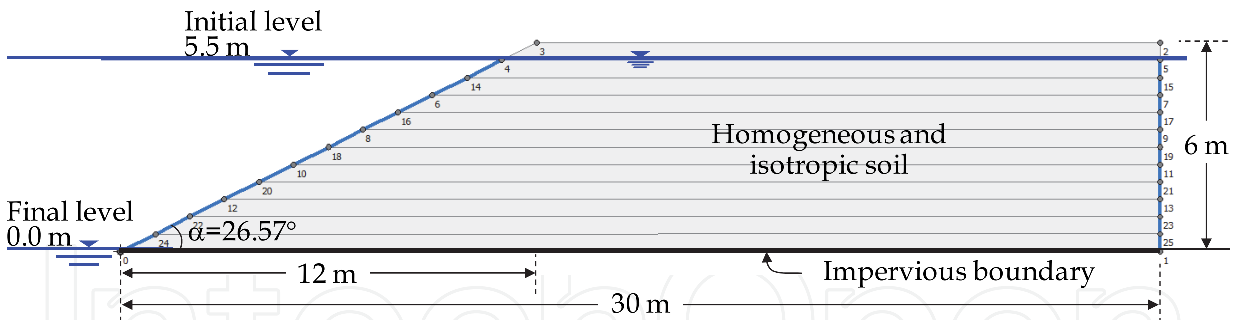


Fig. 13. Simplified geometry and boundary conditions of the studied embankment (Auvinet & Lopez-Acosta, 2010)

From results of analyses (Auvinet & Lopez-Acosta, 2010), Figure 14 shows, for a typical time interval during drawdown (t=4 d), the free surface line which separates unsaturated material (upper part) from saturated material. Variation of this free surface, called *desaturation line* (for drawdown), obtained at different time intervals during rapid drawdown is illustrated in Figure15. Other authors prefer to call it *phreatic line* (Huang & Jia, 2009; Lam & Fredlund 1984; Lam et al., 1987). It must be underlined that this free surface line is not rigorously a flow line since velocity vectors cross it (see Figs. 16a and b). In the same way, results from analysis demonstrate that during drawdown, when water surface descends, large velocities are generated at the contact between the level of water and the slope (which are proportional to hydraulic gradients, and consequently to seepage forces in that zone); these velocities can facilitate local "piping" of material of these regions and jeopardize slope stability. The existence of this maximum flow velocity close to the slope and under the level of water can be observed in Figures 16a and 16b (Auvinet & Lopez-Acosta, 2010).

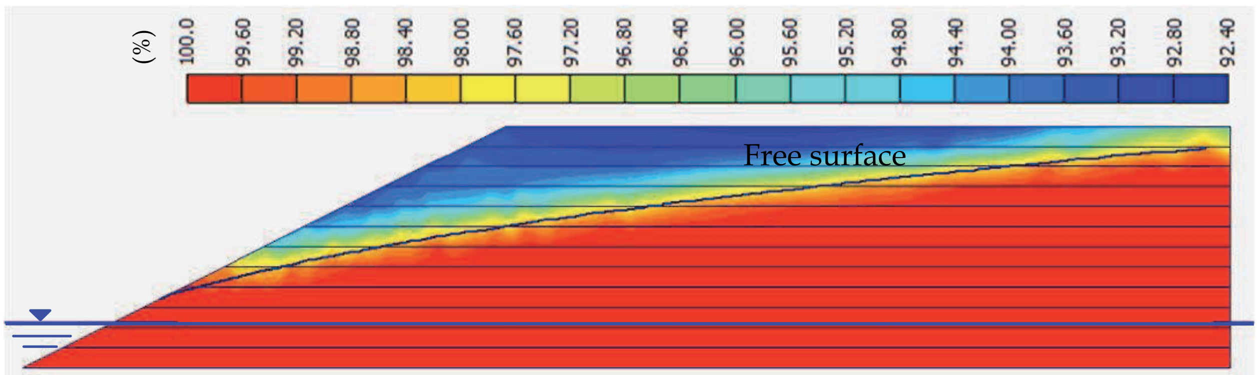


Fig. 14. Variation of degree of saturation for t = 4 d (345200 s) (Auvinet & Lopez-Acosta, 2010)

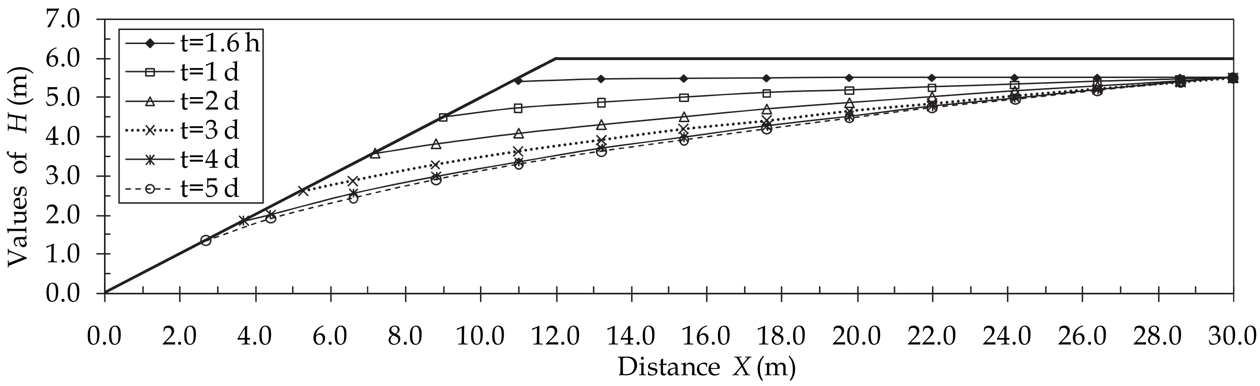


Fig. 15. Variation of *desaturation line* at different time intervals during rapid drawdown (Auvinet & Lopez-Acosta, 2010)

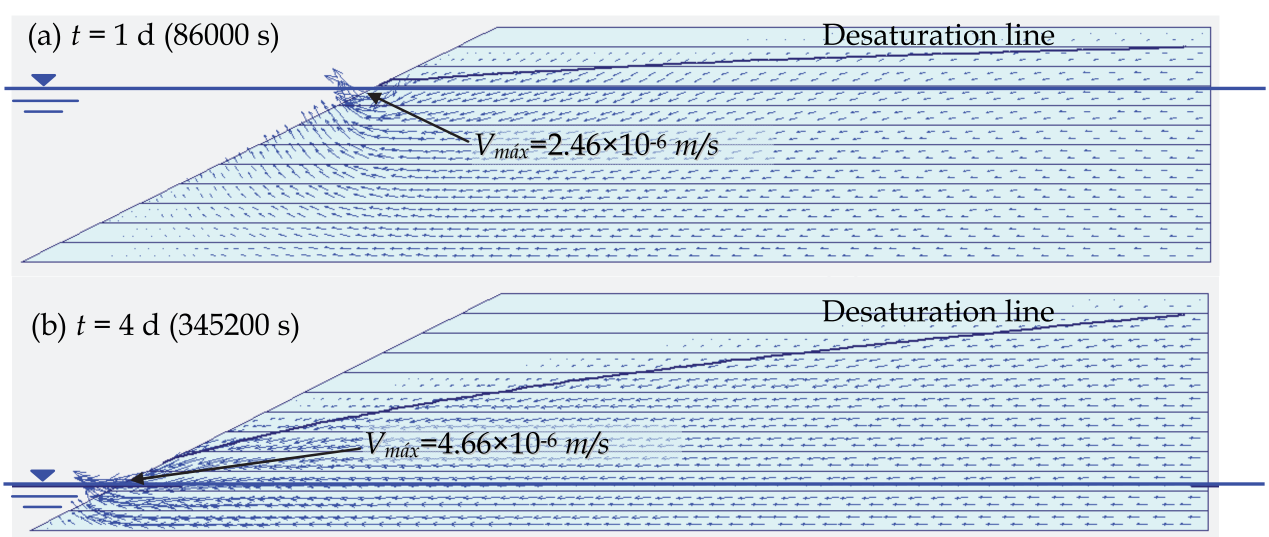


Fig. 16. Velocity vectors (magnitude) for two different time intervals during rapid drawdown (Auvinet & Lopez-Acosta, 2010)

Figure 17 shows the maximum exit hydraulic gradient (i_{max}=0.499) reached at the toe of slope at the end of the rapid drawdown (t=5 d). Additionally, Figure 18 illustrates how the free surface line and velocity vectors change due to the placement of a horizontal drain inside the embankment (Lezama, 2010). The most conspicuous difference can be observed in the reduction of hydraulic gradient at the toe of slope at the end of rapid drawdown (t=5 d), from i_{max}=0.499 to i_{max}=0.25. This demonstrates the usefulness of placing drains in order to reduce soil erosion problems in earth structures.

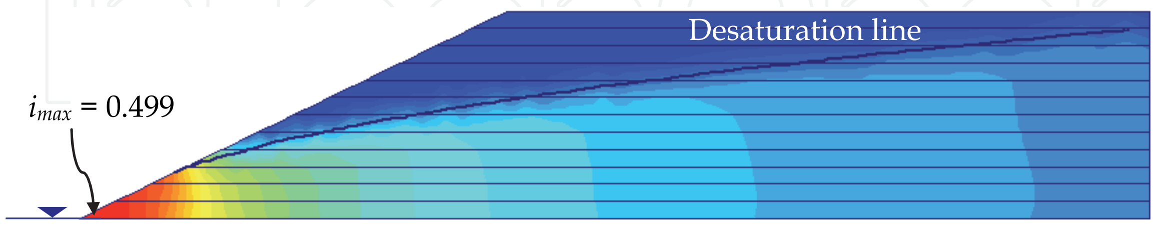


Fig. 17. Hydraulic gradients (magnitude) at the end of rapid drawdown (t=5 d) (Lezama, 2010)

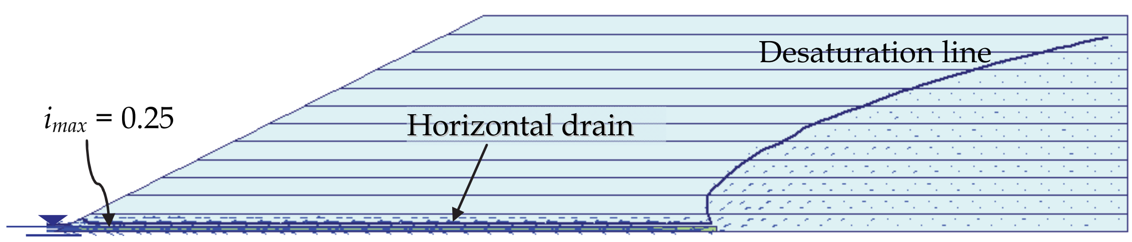


Fig. 18. Changing in velocity vectors and reduction of hydraulic gradient (magnitude) at the end of rapid drawdown (t=5 d) due to the placement of a horizontal drain into the levee (Lezama, 2010)

8.3 Analysis considering both rapid filling and drawdown phenomena

This example focuses on studying the effects on soil erosion due to transient flow within a levee as water level of a river increases and decreases because of the rain cycles in a tropical region. Simplified geometry of studied domain including foundation soil of the levee is illustrated in Figure 19. Properties of materials are specified in Table 3 (Lopez-Acosta et al., 2010).

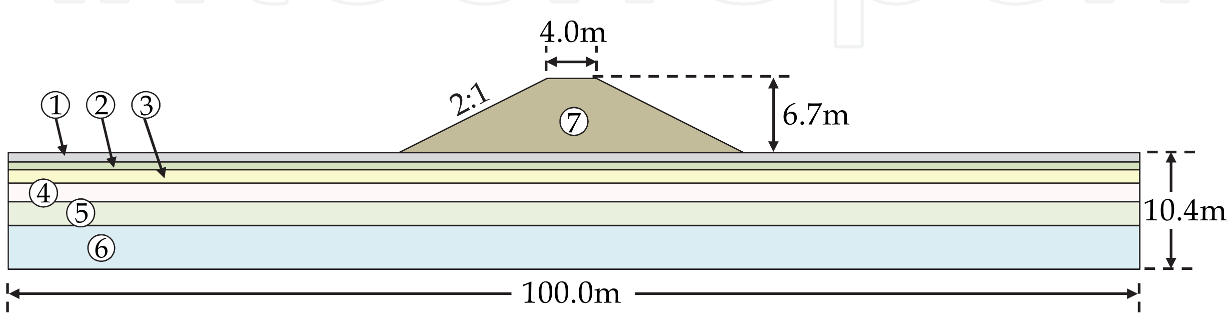


Fig. 19. Simplified geometry and material number of the studied domain (Lopez-Acosta et al., 2010)

N°	Material	Hydraulic conductivity, *k*	Void ratio, *e*
1	Clay sand (SC)	0.0864 m/d (1×10^{-6} m/s)	0.43
2	Sandy clay of low plasticity (CL)	0.0864 m/d (1×10^{-6} m/s)	0.50
3	Organic sandy-clay silt of high plasticity (OH)	0.00864 m/d (1×10^{-7} m/s)	0.90
4	Clay sand (SC)	0.0864 m/d (1×10^{-6} m/s)	0.43
5	Silty sand (SM)	0.0864 m/d (1×10^{-6} m/s)	0.43
6	Organic clay of high plasticity (OH)	0.00864 m/d (1×10^{-7} m/s)	0.90
7	Clay levee	0.00864 m/d (1×10^{-7} m/s)	0.70

Table 3. Properties of material layers (Lopez-Acosta et al., 2010)

Boundary conditions assumed for analyses were as follows:

- For *filling*: water surface ascends from initial level of 13.7m up to maximum level of 16.4m, in a period of 17 days (variation is illustrated in Figure 20).
- For *drawdown:* water surface descends from maximum level of 16.4m up to final level of 11.3m, in a period of 27 days (variation is shown in Figure 20).

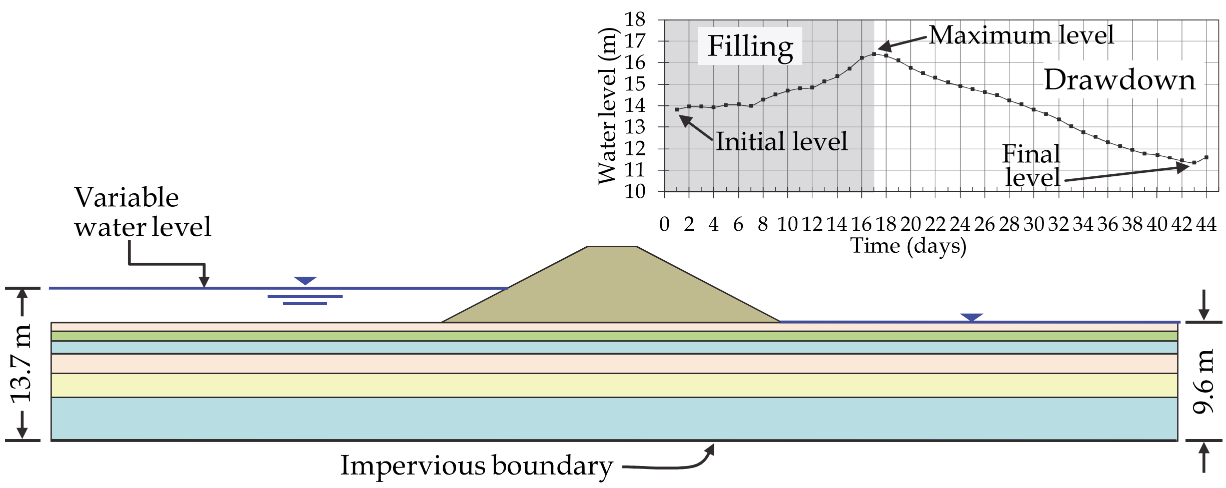


Fig. 20. Boundary conditions assumed for analyses (Lopez-Acosta et al., 2010)

From results of analyses (Lopez-Acosta et al., 2010), it is interesting to note that during transient flow certain regions of higher hydraulic gradients and flow velocities are generated, as appreciated in Figures 21 and 22, respectively. Predominantly, the highest values of hydraulic gradients and velocities take place at the toe of downstream slope of levee. Specifically, the gradient values of those areas greater than the so-called critical gradient (>1) could facilitate *global piping* through the body of levee or through the foundation soil (Figure 21). These above mentioned highest values occur when maximum level of water surface is achieved (day 17 of filling). Additionally, it can be observed that during rapid filling velocity vectors are directed towards downstream (Figure 22a) and during rapid drawdown the direction of some of these vectors changes towards upstream (Figure 22b). Particularly, during rapid drawdown it can be observed that velocities and gradients generated near the upstream slope, as water level descends, are not negligible; in extreme conditions they could facilitate *local erosion* of material in those zones (Lopez-Acosta et al., 2010).

In the same way, from Figures 21 and 22, it can also be observed that in general the highest values of flow velocity occur in the more pervious materials of the studied domain; in contrast, the highest values of hydraulic gradient arise in the less pervious materials of this domain. This is a suggestion that instability problems of levees could not be solved by constructing them with more impervious material, but rather building them with more or less pervious material or even placing drains in strategic areas of the body of levees (Lopez-Acosta et al., 2010). Some authors have indeed concluded that soils with a low hydraulic conductivity, such as clayey and silty soils, are more prone to slope failure than more pervious materials such as granular soils (Pradel & Raad, 1993).
Based on previous results, it can be said that in the case of slope stability analysis, it should be considered on the one hand, the susceptibility to erosion of the material used for constructing the levee; but on the other one, the analysis must also consider measures to decrease the hydraulic gradients and seepage forces generated within the soil mass.
Quite recently, some types of analyses based on probabilistic methods have been suggested for the study of levees in general. Hubel et al. (2010) presented a practical approach to assess combined levee erosion, seepage forces, and slope stability failure modes; they developed response curves for landside and waterside slope stability, as well as landside seepage failure modes for various hydrostatic water loads. In a similar context, the Army Corps of Engineers (Lee & Wibowo, 2007, as cited in Hubel et al., 2010) used the limit state approach for estimating the probability of levee erosion that might induce a breaching failure.

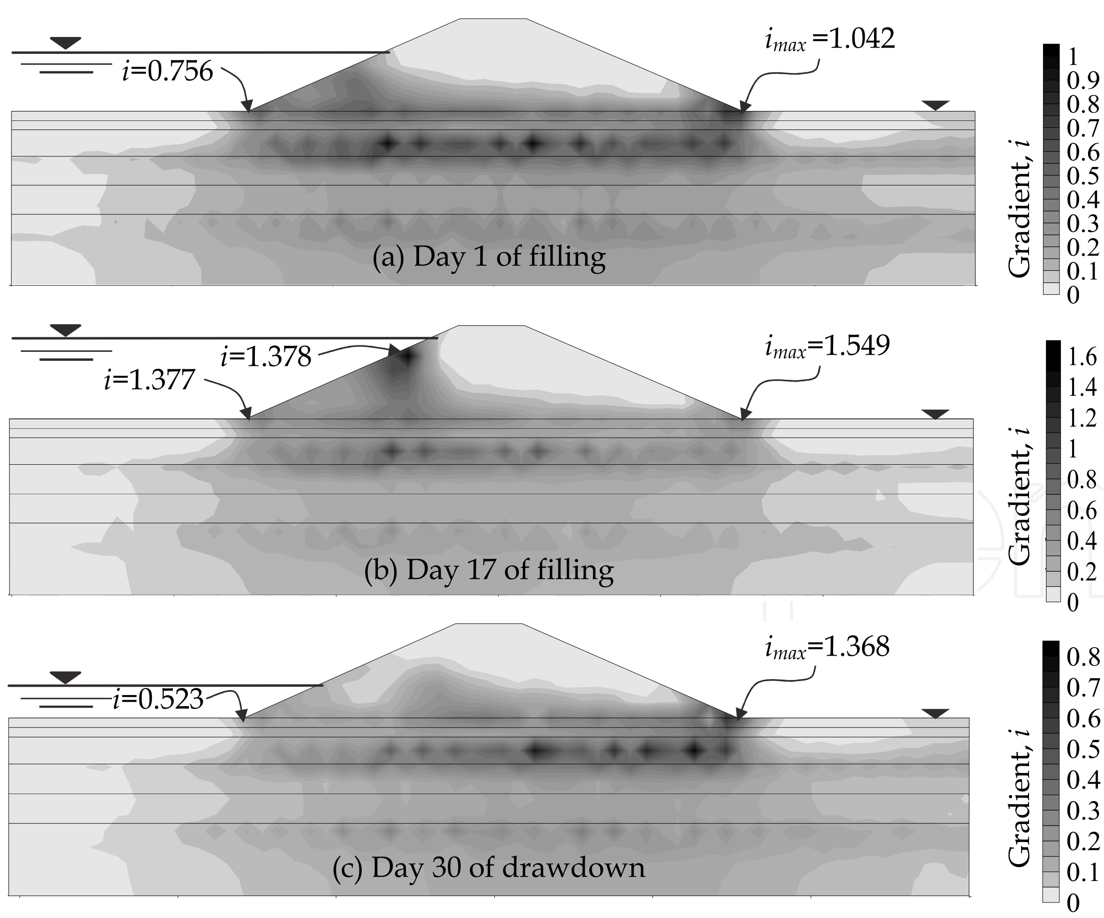


Fig. 21. Hydraulic gradients (magnitude) for three different times during rapid filling and drawdown (Lopez-Acosta et al., 2010)

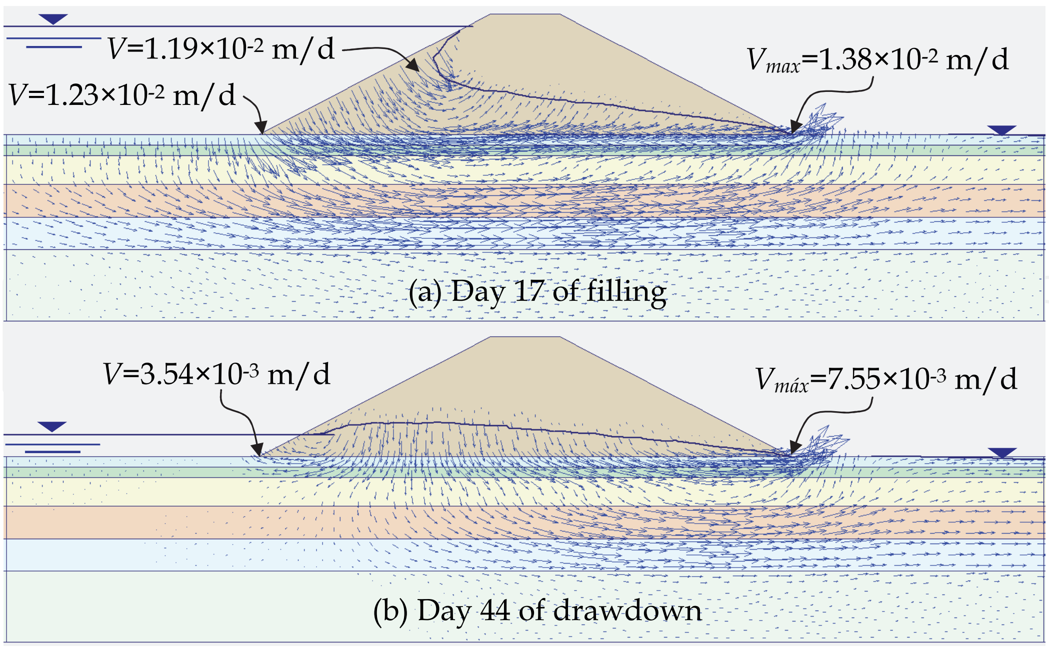


Fig. 22. Velocity vectors (magnitude) for two different time intervals during rapid filling and drawdown (exaggerated scale) (Lopez-Acosta et al., 2010)

9. Conclusions and recommendations

The main conclusions and recommendations derived from this chapter are the following:

- If internal erosion caused by water flow or seepage through earth dams, levees, and other earth structures that contain water is not detected in time and if corrective actions are not taken to stop or control such erosion, the consequences may be a complete failure of that structure.
- The process of soil erosion might occur through the mass of the earth structure or through its foundation. The initiation of this process usually starts at the exit point of the seepage and retrogressive erosion results in the formation of a "pipe".
- The main factors that affect the erosion phenomenon are: a) the erodibility of the soil; b) the water velocity inside the soil mass; c) geometry of the earth structure. The erodibility of the soil depends on several factors, such as water content, plasticity index, undrained shear strength, mean grain size, percent passing #200, soil clay minerals, soil dispersion ratio, water salinity, soil pH and water pH, among other factors.
- The seepage forces that affect the erosion problem are related to the hydraulic gradient that exists in the soil mass. This gradient might be computed and analyzed through the graphical flow net method or through one of the numerical methods that exist in the literature.
- Several procedures and practical recommendations were presented for preventing damages due to soil erosion. Among those are: a) Obtain the best selection of available construction materials; b) Control the homogeneity of the materials during the construction process; c) Use transition zones between the coarse and fine materials; d) Use properly designed filters and drains for all earth facilities exposed to damaging actions of water in their foundations or around the impervious core.
- The erodibility of soils might be analyzed through laboratory and field tests. Some of the most common of these tests were mentioned in this chapter, particularly the ones related to the identification of dispersive soils.

- The applicability of the concepts presented in this chapter was illustrated through some examples related to the analysis of soil erosion problems caused by rapid filling and drawdown conditions in earth embankments.

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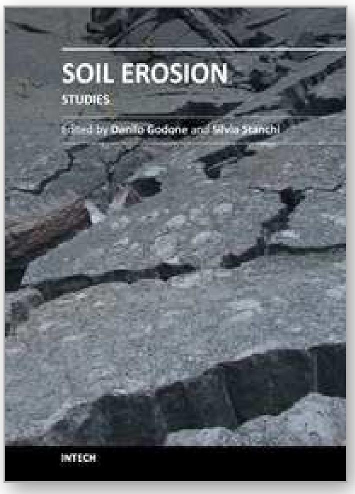

Soil Erosion Studies

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Soil erosion affects a large part of the Earth surface, and accelerated soil erosion is recognized as one of the main soil threats, compromising soil productive and protective functions. The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena. The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems, ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering). The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.).