A review of slopes stability challenges and neighbour buildings

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Abstract. Due to the attraction of the hilly views and lack of flatland in some countries, there are needs to the construction near the slopes. In evaluating slope stability, attention must be considered by geotechnical engineers, particularly to geology, surface drainage, groundwater, and soil shear strength. Slope failures depend on the soil type, soil stratification, groundwater, seepage, and the slope geometry and some failures are sudden and disastrous. The analysis of slope stability is more complicated with the existence of earthquakes, neighbour buildings or structures, unsaturated-saturated soil states. This paper reviews the effect of different parameters on the stability analysis of slopes and neighbour structures. There are distinguished effects from increasing the seismic forces and wetting process on the decreasing of soil shear strength and collapsing of the slopes.

1. Introduction
Flatlands lack and fast urbanization in hilly regions of attractive views are affecting the construction on hill slopes as well as there are many urban excavations process near to existing construction [1].

Slope instability may be attributed to construction activities, erosion, rainfall, seismic forces, and geological features and the slope stability analyses are established on assumptions, where the design of a slope be dependent on experience and accurate investigation (stratification, faults, … etc.) [2].

Slope stability and near foundations are challenging in geotechnical engineering for the reason that the slope stability and bearing capacity of the foundation must be considered [3]. The governing agencies for construction, in some countries, deal with the effects of the building’s height and mass on slopes, but various current standards and codes give emphasis to the design of the buildings in flat areas, with inadequate regulation of buildings design on hill slopes and generally, the existing works on slope stability are for the slopes under distributed loading (oversimplified approach) [4].

Large earthquakes are essential in slope failures [5]. In the recent construction, the reliability of buildings’ stability must be ensured for seismic forces where there is a decrease in soil bearing capacity and an increase in deformation [6].

A lot of earth slopes are in unsaturated condition, with negative pore water pressures (PWP) beyond the water level, which can enhance the stability of slopes [7]. The rainwater infiltration will be lessening the matric suction and the soil’s strength, which may cause slope damage [8].

This paper discusses and reviews the challenges of the above different conditions on the stability of the slopes.
2. Slopes Types and Analysis
The earth slopes can be classified as natural or man-made slopes, and the slopes may be infinite or finite depending on the slope height [9].

2.1 Types and Sources of Slopes Failure
There are five major categories of slope failures, fall, topple (forward rotation of slope mass), slide, spread (by a unexpected movement of sands and silts stratum water-bearing and loaded by fills) and flow (soil mass acts as a viscous fluid) [10]. Numerous failures result from unrevealed geological features. A thin seam of silt (for example, stratified soils), external loading, construction activities and rapid drawdown of reservoirs [2].

2.2 Factor of Safety
The stability of slopes can be evaluated using the following methods 1) the limit equilibrium, 2) limit analysis, 3) the finite difference and 4) the finite element [2]. The factor of safety of slopes is the charge of the geotechnical engineer. Generally, in the limit equilibrium method, the factor of safety is defined as in Eqs. 1 to 9 for planar slip surface [9,11].

\[
F_s = \frac{\tau_f}{\tau_d}
\]  
(1)

Where:

\[
\tau_f = c' + \sigma' \tan \phi'
\]  
(2)

Where: \(c'\) is the effective cohesion, \(\sigma'\) is the normal effective stress on the surface of rupture, \(\phi'\) is the effective internal friction angle, and:

\[
\tau_d = c'_d + \sigma' \tan \phi'_d
\]  
(3)

Where: \(\tau_d\), \(c'_d\) and \(\phi'_d\) are the mobilized soil characteristics in shearing stress, so, the factor of safety will be:

\[
F_s = \frac{c' + \sigma' \tan \phi'}{c'_d + \sigma' \tan \phi'_d}
\]  
(4)

and it could be written as:

\[
F_{cr} = \frac{c'}{c'_d}
\]  
(5)

and

\[
F_{\phi'} = \frac{\tan \phi'}{\tan \phi'_d}
\]  
(6)

When \(F_{\phi'}\) turn out to be equal to \(F_{cr}\) it will give the factor of safety related to strength. Then we could say \(F_s = F_{cr} = F_{\phi'}\) and when \(F_s\) is equal to 1, the slope will be in an impending failure state.

The factor of safety for infinite slopes in soils is as in Eq. 7.

\[
F_s = \left(\frac{c'}{\gamma \cdot H} \cdot \left(\frac{1}{\cos \beta \cdot \sin \beta}\right) + \frac{\tan \phi'}{\tan \beta}\right)
\]  
(7)

Where \(\beta\) is the angle of the slope. For uncedemented, normally consolidated clays and sands, \(c'=0\). For partially saturated soil, \(c'\) will be due to soil suction (i.e., negative pore water pressure) only.

For infinite slope with seepage parallel to slope, the factor of safety as in Eq. 8.

\[
F_s = \left(\frac{c'}{\gamma_{sat} \cdot H} \cdot \left(\frac{1}{\cos \beta \cdot \sin \beta}\right) + \left(\frac{\gamma'}{\gamma_{sat}}\right) \cdot \frac{\tan \phi'}{\tan \beta}\right)
\]  
(8)
While for slope with groundwater not at the ground level (flowing partially), the Eq. 8 will be as in Eq. 9.

\[ F_s = \left( \frac{c'}{y_{sat.H}} \right) \left( \frac{1}{\cos \beta \sin \beta} \right) + \left( 1 - \frac{\gamma w w}{\gamma_{sat.H}} \right) \left( \frac{\tan \beta'}{\tan \beta} \right) \tag{9} \]

For finite extent slope, a two-dimensional rotational slip surface is adopted for the analysis of slope stability. Bishop (1955) assumed a circular slip surface is relating to the moment equilibrium and Janbu (1973) assumed a non-circular slip surface and it is depending on the force equilibrium and a method of slices is adopted to define the location of the slip surface [2]. There are many other methods developed using the moment and force equilibrium where the factor of safety localized at the intersection of the variation of both equilibrium versus lambda, such as Spencer (1967), Morgenstern-Price (1965) and Sarma (1973) [12].

In the numerical analysis of slope stability, the easier method of soil failure modelling is the Mohr-Coulomb model (MC or called “elastic-perfectly plastic”). This method provides lower values than the Modified Cam-Clay model (MCC or called “elastoplastic model”) for all investigated parameters of the dam and foundation soil [13,14,15].

3. Effect of Neighbour Structures

Speedy expansion and the insufficiency of flat land near hilly districts are driving people to construct on or near slopes whereas the foundations are regularly constructed at different levels due to limited and restricted areas [4]. There are a lot of urban excavations which are done adjacent to existing buildings. The stability of such a system needs to be studied due to the reducing effect of the excavation, so, the bearing capacity may decline drastically and as the retaining system is usually neglected in this stage, the foundation and the adjacent building will be unstable [1].

The safety of foundations next to slopes is a challenging issue because both slope stability and bearing capacity have to be considered [3]. Loads on the crest of a slope increase to the gravitational load and may lead to slope failure [2]. For footing-on-slope, the limit equilibrium method is simple and applicable with the different complicated parameters, such as loading, geometry, characteristics of soil, but, this method is less accurate than other methods, such as the slip-line and bounds theorems of limit analysis, while the slip-line is difficult to use in problems with complex loading conditions or geometries, and bounds methods (upper and lower bounds) [3].

There are few studies on the effect of loading on slope stability. Most accomplishment codes endorse the use of pseudo-static procedures and approval of a minimum factor of safety for the stability [16,17,18] and there are codes allowing extra use of displacement-based procedures for the assessment [18,19]. Numerous standards/codes mainly emphasize the design of foundations in flat districts, with only inadequate regulations for the buildings on slopes [4].

Eq. 10 is regularized limit stress as a function of dimensionless factors relating to the stability of the system (foundation near slope), where \( P \) is limit stress (average) under the foundation, \( B \) is the width of the foundation, \( a \) is the distance between the foundation and the slope crest, \( \beta \) is the angle of the slope, \( C \) and \( \varnothing \) are the soil properties [3].

\[ \frac{P}{y_B} = f \left( \frac{\beta}{\varnothing_B}, a, \frac{H}{y_B}, \frac{C}{\varnothing_B}, \varnothing \right) \tag{10} \]

4. Effect of Seismic Forces

Different forms of seismic waves are generated when an earthquake happens. Compressed (P), Shear (S), Rayleigh (R) and Love (L) waves are the major seismic wave forms [20]. Earthquakes shear forces decrease the soil stiffness and shear strength where at saturated condition, the pore water pressure could be the same to total stress and the soil will acts as a viscous fluid (liquefaction) due to undrained condition [2].

The features, such as the scale of the earthquake, the frequency and intensity of ground motion and the duration of a heavy shaking are important in input parameters [21]. The tensile stress field causes the normal fault, on the contrary, the compressive stress field creates the reverse fault [22].
The earthquake mainly yields enormous destruction to slopes [23]. Due to variations in external stresses and groundwater levels, shear stress is created in stabilized slopes leading to the slope collapse [24]. One of the most serious events is the 1970 Peru earthquake with 54,000 people were killed and buried in two cities [25]. Many landslides in 1920 due to the Haiyuan earthquake killed at least 100,000 people [26]. In 2017, an earthquake crash into the Iraq Iran border killing more than 530 people and injuring thousands in Iran alone [27].

The slope stability analysis with seismic forces is more complicated than the static analysis [28]. The analytical methods to estimate the seismic slope stability are in three groups: the pseudo-static [29], Newmark’s sliding-block analysis [30], and numerical methods [31]. Pseudo-static is believed to be acceptable for soils of no high pore-water pressure or major strength decrease under cyclic loading or for locations of no sudden variations in geometry and geology [19].

5. Effect of Soil Wetting
There are many soil initial properties that affect the collapse behavior, such as moisture content, soaking pressure, vertical stress and duration of application, void ratio, cementation, and suction [32,33].

Recent research has established that the unsaturated soil state is always present in collapsible soils, and large deformation and volume changes happen as a product of the decrease in the matric suction, in which the main cause of the collapse is the wetting process under constant net pressure [34,35,36]. For an unsaturated stable earth slope, the soil is subjected to frequent cycles of wetting and drying due to infiltration, evaporation and rise and decrease of the groundwater [37]. Long term soaking process can improve the shear strength of the soil [38,39]. The higher collapse potential is due to the higher wetting duration of the soil prior to loading [40,41]. The soil shear strength (τ) is suggested to be related to the unsaturated stress state variables, as in Eq. 11 [42].

\[ \tau = c' + (\sigma - u_a)\tan \theta' + (u_a - u_w)\tan \theta_b \]  

(11)

where \( u_a \) is the pressure of pore air, \( u_w \) is the pressure of pore water and \( (u_a - u_w) \) defines the matric suction. This equation assumes the internal friction angle (\( \theta' \)) remains constant under saturated and unsaturated conditions [43]. The angle \( \theta_b \) represents the suction effect and it is calculated from shear strength (\( \tau \)) versus matric suction \( (u_a - u_w) \) plot [44].

A planar slip surface is adopted for an infinite slope model in unsaturated slope stability analysis within the previous decades [45]. But infinite slope analysis is simply true when the depth of the slip is far less than the length of the slip as a result of the neglecting of boundary effects [37]. The theory of slope stability for unsaturated soils can be considered as slope stability theory continue for saturated soil and depending on General Limit Equilibrium (GLE), a method is recommended for estimating the factor of safety with respect to force equilibrium, Eq. 12 generalizes the safety factor in terms of the unsaturated parameters, as in [46].

\[ F_s = \frac{l[c' + (\sigma - u_a)\tan \theta' + (u_a - u_w)\tan \theta_b]}{\tau} \]  

(12)

Soil suction is varied greatly above the water table in sandy soils [45]. Due to a reduction in soil matric suction, the potential of collapse increases in all soil types [47,48]. The initial saturation degree is the major influencing factor on the collapse activity of soil in an unsaturated state and as well as the collapse potential reduces with an increase in the density of the soil [49]. For the prediction of the soil settlement, the remoulding sizing affects the resulted value and trend of settlement, the cylindrical samples (as in Oedometer) give a strong trend and trusted values [50]. The time required to achieve the zero matric suction increased related to the initial soil dry density increase [51]. For the soaking period of 6hrs, 15–60 % of the settlement ratio of soils occurred during the first minute, whilst only 2–15 % for the treated soils by acrylate liquid within same time [52].

Drawdown of the water table is a condition of drying state where the rapid drawdown is a hazardous condition. The factor of safety against sliding decreased a little within the short period after the start of rapid drawdown of water in the reservoir, then started to increase [53,54].
6. Summary and Conclusions

The present research aims to review the challenges of slope stability and neighbour buildings with the existence of seismic forces and wetting processes in unsaturated soil conditions. The following points are stated:

1. There are many analytical and numerical methods to estimate the safety factor of the slopes and a method of slices is adopted to define the location of the slip surface.
2. In the numerical analysis of slope stability, the easier method of soil failure modelling is the Mohr-Coulomb model (elastic-perfectly plastic) with lower values than the others.
3. The analysis of the stability of the slopes and the adjacent foundation is complicated due to the interaction between overall slope stability and soil bearing capacity. There is a need to develop a detailed code/guider for the design of footings on the slopes.
4. Eq. 10 is regularized limit stress as a function of dimensionless factors relating to the stability of the system (foundation near slope).
5. Due to the different stresses, the analysis of the slope stability with an earthquake is not easy. The analytical methods to estimate the seismic slope stability are in three groups: the pseudo-static, Newmark’s sliding-block analysis and numerical method.
6. The slopes are dry in nature, with the wetting process, the soil well loses the shear strength besides the decrease due to the solution of the bonding materials.
7. Eq. 12 generalizes the safety factor in terms of the unsaturated parameters.

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