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Effects of Landslides and Soil Settlements on the Built Environment: A Meta-analysis

Nikolaos Alamanis[1], Grigorios Papageorgiou[1], Nikolaos Xafoulis[2] and Ioannis Chouliaras[1]

[1]General Department, University of Thessaly, Larisa, Greece, 41500
[2]Laboratory of Ecohydraulics& Inland Water Management, Department of Ichthyology & Aquatic Environment, University of Thessaly, Nea Ionia Magnisias, Greece, 38446
alam@uth.gr

ABSTRACT

One of the most important problems that Civil and Geotechnical Engineers' Society faces, stand for the settlements due to inconsistent permeability of soil, not only in building projects but also in constructions in general. Settlements observed are usually a function of both the imposed load and the characteristics of the foundation soil [1]. On each slope, the difference in level and in slope gradient in combination with the gravitational forces and the possible presence of groundwater, create shear stresses inside the slopes, which are countered by the shear resistance of the soil. When the developing stresses overcome shear resistance, then they lead to a fracture of the slopes and to a landslide. The instability of slopes, leading to the displacement of soil mass downstream known as landslide, constitutes a significant risk to human activities and is often accompanied by the destruction of property, injury and loss of life. So, landslides and soil retreats are of the most significant catastrophic phenomena recorded on the surface of the earth. The above-mentioned phenomena can be a major threat not only to the social and economic fabric, i.e. the quality of life of a region, but also for the environment (basin-filling reservoirs, clogging of streams – rivers, road surface retreat, destruction of forests and ecosystems, etc.). The main objective of this work is to investigate the environmental impact of the failure of the slopes and soil settlements, particularly in cases observed in Greece, as well as the prevention and stabilization measures against landslides and loose soils, mainly through mild environmental interventions.

Key words: Failure of slopes, landslides, soil settlements, road settlements, environmental impacts, protective measures.

INTRODUCTION

By the term landslide we refer to the slow or rapid downward movement of a soil mass due to gravity. A landslide is triggered when the shear stresses developed inside the soil exceed those with which the soil can resist. Landslides can be caused by the liquefaction of fine grain silt sand layers, or due to a general failure, in combination with increased loads due to an earthquake, increased pore pressure and reduction in the available shear strength of the soil. In particular, our country, which is characterized by complexity of geological structure and tectonic stress, has in the past suffered and still suffers constantly from the effects of the outbreak of such destructive phenomena. The need therefore to assess stability has led to the development of analytical methods pertaining to either two or three dimensions. For this reason, it is important to know the types of landslides, as well as the failure mechanisms they present, in order to proceed with the analysis of stability and the calculation of a satisfactory safety factor. The types of failure typically encountered during loss of stability are shown in Fig. 1.

METHODOLOGY

In the introduction and in section 3 there is a historical and general reference to important landslides and damage that they have been sustained by several structures. Subsequently, in section 4 detailed settlement cases are presented as well as liquefaction phenomena which have occurred after earthquake shaking. Measures for retaining slopes and strengthening loose soils are presented and suggested in sections 5 and 6. Further sections 7 and 8 provide suggestions and conclusions drawn from the above research. Finally, a reach bibliography reference is used in section 9 to enrich the theoretical background of this research. Moreover, it should be noted that this paper is heavily based on previous work done by the author team, with references included in the bibliography where referencing is due. More specifically, the papers upon which this present paper stems from, constitute numbers [2], [3], and [4] in the reference list. This combination of papers was deemed to be the most beneficial in providing new insights in the search for protection measures against landslides, as well as the methods for improvement of loose soils.

SLOPE FAILURE CASES

Below are some examples of landslides as well as failures of slopes and dams.

a. Taiwan Landslide

Natural failures, where and when they occur, cause serious techno-economic and environmental disasters, such as those in Fig. 2 on motorway No. 3 of Taiwan, and call for an urgent solution to the problem.

Fig. 1 Slope failure on motorway No. 3 of Taiwan (2010). For the removal of the soil, 50 excavators, 100 trucks and 1000 workers had to be used for 20 days [5]

b. Landslide of Malakasa

Early in the morning of February 18th, 1995, a massive landslide took place on the 36th km mark of the Athens - Lamia road. Extensive damage was caused by this movement of the slopes, resulting in the disruption of road and rail communications of the capital with the northern part of Greece.

Fig. 2 The deformation of the railway line from the landslide of Malakasa [6].

c. Niigata-Ken Chuetsu (Japan) Earthquake

On October 23, 2004 the above-mentioned region in Japan sustained a 6.6 R earthquake. Extensive damage was recorded in the transportation networks, as well as in forest areas, mainly due to soil failures because of landslides.

Fig. 3 Road destruction in the Nigata-Ken Chuetsu (Japan) earthquake [7]

d. Failure in the spillway of the Shih-Kang Dam

The Chi-Chi earthquake took place on September 21, 1999 in the Chi-Chi area, which is part of Taiwan's western city of Nantou. It is worth mentioning that 2,415 deaths, 11,305 injuries were recorded in this earthquake, and more than 100,000 people became homeless after the earthquake, with the value of the damage being estimated at 10 billion dollars. The Shih-Kang Dam sustained a vertical displacement in the spillways in the order of 10-11m). In order to understand the magnitude of the disaster, it is worth mentioning that the overflows are made of concrete with a height of 12.5m and a width of 36m.

Fig. 4 Failure in the spillway of Shih-Kang Dam [8]

SOIL SETTLEMENT CASES

Below are some examples of soil settlements.

a) Village of Ropotos of Trikala

The strong morphological relief, the presence of formations characterized by low consistency, the intense penetration of the area from source and surface waters, is among the causes of the landslide movements that affected the village of Ropotos of Trikala. More specifically the water of the rains that fall in a short period of time on sensitive geological highlands, infuse the ground, causing both on the surface and beneath it, large, visible or invisible cracks and settlements (Fig. 5).

Fig. 5 Settlement in the village of Ropotos, Trikala [9]

b) Liquefaction phenomena in Ilia-Achaia

The Mw 6.4 earthquake that occurred in June 8, 2008 near the city of Patras, Greece, was the reason for large-scale settlements of infrastructures, along with geotechnical failures in a 25 km area around the epicenter [10, 11]. Such defects entail liquefaction of the ground, in several cases combined with lateral distribution, slope instabilities, rockfalls and coastal anomalies [12]. Liquefaction phenomena occurring in the event of the earthquake, in Ilia-Achaia (8th June 2008) in the eastern part of the beach of Kato Achaia, occupy an area of 150x90 m^2, at about 30 m from the shoreline and were perceived by the appearance of sand craters and cracks, with or without emergence of fine-grained silt [13].

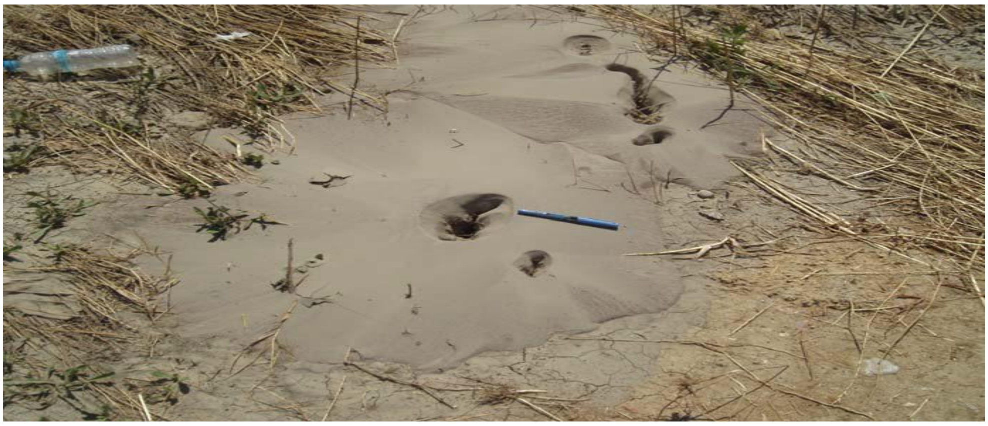

Fig. 6 Kato Achaia-East: Sand craters with the emergence of the liquefied soil of silt composition [12, 14]

c) Settlements in the region of Larissa

The current piezometric situation with the weakened hydraulic load, mainly in the horizontal vectorial direction, due to overexploitation of the groundwater potential showed that: the drainage of the horizons in the deeper aquifers is quite weakened to nonexistent. Seasonal piezometric fluctuations of 3-6 m which were before the system entered full use (1970's) are converted to 40-50 m with a continuously dropping annual water level. Water formations, which have developed in depth in the basin of Larissa, are essentially medium and fine grain sands and gravel (medium water conductivity 10-3–10-4 and 10-5 m/sec) located in interplay with large clay and clay packages. As a consequence of this, we observe consolidation of fine-grained materials of the rectangular-shaped soil mass with the long side of the NW-SE direction. The alluvial granular formations attempt to adapt to the new equilibrium state created by the fall of the groundwater level by compression, i.e. by reducing the voids between the grains [15].

Fig. 7 Cracking on road surface and a house courtyard [16, 17]

Measures for retaining and strengthening slopes

a) Restraining Measures

A prerequisite for the safe construction of a retaining system, is the geotechnical survey [18], though which the following should be ascertained:

- The existence or absence of loose or soft soil materials with potential instability problems during the excavation construction of the retaining elements.
- The existence of highly permeable soil formations (such as sands, gravel, etc.)
- The presence of rocky formations or bulges which could cause difficulties in excavating or drilling the retaining elements.
- The presence of underground aquifers and its level.

b) Support Measures

Geogrids are used as a substitute for natural arming materials, to comprehend progressively complex geotechnical issues [19]. They are isolated into uniaxial and biaxial (and the most recent innovation is triaxial) and are basically made of high thickness polyethylene (HDPE), polypropylene (PP) and polyester with a PVC covering. The geogrids are utilized:

- For the support of the bank in feeble subsoil or even the dike itself.
- For the development of strengthened earth dividers with soak (up to 90°) inclines.
- For the construction of reinforced granular bands for the distribution of loads in arrays of piles.
- To arm the ballast or substrate in railway works.
- For reinforcement of road-surfacing on older cracked surfaces, in order to avoid 'reflective' cracks.
- To strengthen the pavement base and subsoil and to reduce their thickness for an equivalent traffic result.
- For anti-erosion protection of unstable soils, in natural or artificial slopes. To prevent the bouncing of detached pieces from rough slopes.

So as to set aside time and cash, it is frequently important to strengthen inclines with the goal that they are steady. It is conceivable to utilize lower quality soil materials and this can help a task in its plan and fundamentally lessen the effect on the earth, making adaptable structures with the least conceivable land occupation. The key benefits of using geogrids are presented below:

- They are environmentally friendly, limiting intervention in environmentally sensitive areas.
- They diminish the measure of required soil materials and permit the utilization of locally accessible soil materials.
- Their construction is simple and quick.

They also present:

- Significant reduction in total costs compared to traditional methods.
- Noteworthy decrease in the thickness of the granular material, without loss of solidarity.
- They help minimize excavation and maintain natural aggregates.
- Improvement of embankment condensation.
- Control of differential subsidence.

c) Drainage methods

Drainage methods for fine clay soils (practically watertight), where the zone affected by drainage is small, do not perform in a satisfactory manner. In this case, soil stabilization is achieved by methods that have been applied in the engineering of foundations and is known as "hardening" of soils. Draining by electrosmosis, has the same practical effect as underground drainage, but differs because water is not drained by gravity but under the influence of the electric field. Cement grouts have good results in surface landslides and in solid materials such as marl, limestone marl, clay marl, which are separated by a dense network of fractures, but cannot be applied to pure clay soils.

Methods of Strengthening Loose Soils in order to avoid settlementsTechniques for improving and enhancing soft soils are comprised of interventions to change the structure of the problematic soil in order to improve its mechanical characteristics and increase its bearing capacity. In general, the strengthening material is applied to soft - loose soils such as:

- loose sands, especially when saturated
- loose and medium density saturated sand and gravel under seismic loading
- uncharged or sub-consolidated clays and mud [20]

The methods utilized are the following:

a) Mechanical Soil Compaction

It is the artificial increase of soil density by mechanical means. Mechanical compaction is applied to soil improvement, on which mainly light constructions are to be erected, ones that are rather not affected by large and uneven settlements. This mechanical compaction reaches a small depth, is achieved by charging, through rolling or tampering, driving of stones or piles into the soil, vibration, through a dynamic method or through soil drainage [21].

Soil compaction is applied to:

- stabilize the soil for the foundation of technical works
- create a more durable terrain for walking and general space formation.
- promote homogenization of foundation soil.
- aid in the creation of solid land plots, the construction of roads, etc.
- provide support in the construction of land barriers.
- improve the carrying capacity and reduce the potential settling of soil excavation materials etc.
- increase passive soil resistance in lateral loads.

Soil compaction manages:

- to increase the shear strength and bearing capacity of the soil.
- to reduce compressibility and therefore all subsequent soil settling in external load conditions.

- to bring about a reduction in soil permeability.
- to increase soil resistance.
- by loading
- by cylinder or tampering
- by inserting gravel, stones, or stakes
- by vibration
- by dynamic method. menard method

Fig. 8 Application of the dynamic compaction method, which consists of dropping large weights onto the ground [20]

Dynamic compaction is implemented on large construction sites and requires heavy equipment. The application of the method is avoided in the case of existing structures at distances less than 30 m, as the vibrations of the ground may cause cracking. Dynamic compaction is particularly suitable for granular (loose sandy) soils; but it can also be applied to mixed terrain of granular and cohesive materials.

The vibrations caused by the drop of the weight are relatively large and require attention in the design and implementation of this method. Before the decision on the application or not of the method for a specific plot, the following should be considered:

- Detailed soil investigation, which includes on-site compressibility tests, Vane tests, compressibility and penetration tests.
- Accurate determination of Atterberg limits, water content and particle size composition, for all layers affected by compaction.
- Complete determination of soil layering, with dense drilling so as to reveal any existing local lenses.
- Compressibility tests on the dynamic "compressor meter".

The area to be compacted must be properly prepared for the machine, which weighs 60 to 200 ton, and should have very good drainage of both rainwater and any water that will rise to the surface because of compaction. The evaluation of compaction is done with a compression and penetration meter, radioisotope methods, measurement of apparent weight, or other suitable methods [21].

b) Soil Drainage

After removal of water from unstable soils, such as wet loamy or clayey ones, their strength is improved. The drainage is usually done through natural flow, or through pumping, but it can also be achieved by direct current in one-inch iron piping driven into the ground, as positive poles, close to adjacent tubular drainage shafts of 210 mm diameter, as negative poles. The flowing electric current drives the water through the very thin soil pores into the well. Preloading is most effective when combined with the use of vertical drainage, which consists of creating vertical columns of increased permeability in the soil, in order to accelerate the consolidation phenomenon (Fig. 2). The drains communicate with a horizontal high permeability layer (e.g. a granular layer on the ground surface under the preloading embankment). In this way the water within the pores flows horizontally toward the nearest drainer and then vertically to the drainage layer (Fig. 9). The method is applied to fine clay soils, in which settlement from secondary consolidation is not significant. The drains may consist either of sandpiles or gravel piles with a usual diameter of 0.50-1.0 m or by geocomplex strip drains, with a usual width of 10 cm.

Fig. 9 Geocomplex vertical drains are placed in the ground by using a special crane with a vertical guide, in close in-between distances of 2-4 m [20]

Soil Consolidation with Chemical Methods

- by chemical substance binders
- by injection of bitumen materials
- injections of suspensions of milled fly ash [22]
- by electrochemical method. Casagrande method

c) Soil Removal

d) Thermal Action

- ground heating,
- cooling

Fig. 10 Soil cooling layout for stabilization [23]

Fig. 11 Application of the cooling method in a deep excavation [23]

e) Strengthening with Arming

The soil can be improved by introducing local arming components. This can be done by inserting metallic strips in the ground (reinforced ground), using geotextiles, and inserting steel rods or by riveting (soil nailing) or by inserting root piles [24].

- armed embankments and armed soil

- geotextiles-geogrids
- geofoam

f) Soil Liquefaction - Reinforcement and Improvement Methods

Non-coherent saturated soil formations, when subjected to direct loading under undrained conditions, tend to compact, but due to their inability to change their volume there is an increase in the pressure of their pore water with simultaneous reduction (or zeroing) of their shear strength. In the above process, the state of these soil layers is converted from the solid into the liquid phase, that is, liquefaction thereof is induced. In order for a soil to be considered potentially liquefiable, it must meet certain conditions, which need to be considered before final assessment of the likelihood of liquefaction for the soil formation under consideration.

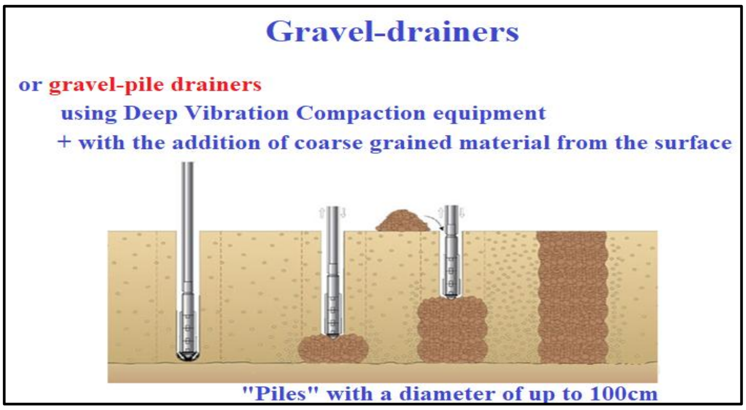

Fig. 12 Complementary action of gravel drains in liquefiable soil [25]

Significant improvement of the liquefied soils is achieved by using gravel-drainage. Their complex action contributes to:

- Acceleration of drainage of water overpressures.
- Soil compaction (sands).
- Load bearing capacity.
- Increase of the equivalent shear strength.

SUGGESTIONS

From the literature review and analysis, measurement and monitoring of the behaviour of many projects in Greece, to which the method of preloading to improve the mechanical characteristics of the foundation soil has been applied, showed that:

i. The use of vertical geotextile drains on both sides to accelerate settling and completion during construction, and to improve the shear properties of foundation soil, is an effective method which offers speed, economy and less impact on the environment than the sandpile method.

ii. Drain-to-ground compatibility tests or similar experience as well as appropriate on-site testing are considered to be essential for the successful economic and technical implementation of vertical geosynthetic drains in each project.

iii. it is considered necessary to build a test embankment before the construction of the project in order to take timely instrumental measurements of soil behaviour and contribution of drains, in order to properly financially decide on the choice of grid systems of drains and to plan efficiently the various phases of construction of the project, particularly in the case of large-scale projects.

iv. Freezing of the soils is resulting in a very large increase in strength, consistent with the formation of a rigid ice skeleton. This increase depends exclusively on the amount of water contained in the mass of the specimens. The higher the water content, the higher the values of mechanical strength. Considering that strength increases with the decrease in temperature, then it is easily understood that the method of cooling with liquid nitrogen (-196 ^{o}C) can lead to the creation of much greater soil strength compared to that observed in laboratory tests in frozen specimens at -14 ^{o}C, similar to that of concrete, as a substantial and secure solution in many geotechnical problems and structures [26].

v. When mixing asphalt and soil, there is no chemical reaction but only improvement of the mechanical characteristics of the soil due:

- To the increase of coherence between grains of soil, resulting in a corresponding increase in load bearing capacity.
- To the decrease in hydropermeability of soil material [27].

Also, the suggested protection and stabilization measures to avoid landslides are the following:

i. The proposed protection measures, which are in the logic of immediate rehabilitation and are considered mild intervention, include retaining structures, extensive excavations and formation of new slopes with low gradients, using benching and vegetation cover in conjunction with a land drainage system throughout the length of failed roads to collect and remove both surface – rain and underground rainwater.
ii. The fall of rocks is very much commonplace on rocky slopes and often has devastating effects on the road network as well as on people in transit. Such accidents have occurred in the area of Kakia Skala (Greece), where very high and steep limestone slopes are located, as well as in the area of Tempi during the construction of the tunnel. In case of activation of small rocks from high level slopes, excavations are carried out on the foot of the slope, parallel to the axis of the motorway, and on the outer side (towards the freeway), a trapping wall is built. This wall prevents the falling rocks from entering the road deck, but it is not always possible to ensure the appropriate width for the pit and the foundation area of the wall. Indicatively, it is reported that for a 33m high slope, an 8m wide and 2m deep trench is required.
iii. A metal mesh that covers the slope surface is used to deal with small scale falling rocks. This, on the one hand, prevents the falling of rocks and, on the other hand, reduces the kinetic energy of any falling ones. Metal nets are used to deal with large-scale rocks, such as Geobrugg type ones [26].

CONCLUSION

On the above presented methods and technics for loose soil improvements, the following conclusions can be pointed out in order to avoid settlements and landslides:

i. The process and method of implementation of soil improvement and reinforcement depends directly on the quality of the soil (sandy, cohesive or expanding soil), the (physical or mechanical) property to be improved, the type and size of the geotechnical project, but also on the corresponding construction. It should be noted that the combination of the above, leading to the selection of the most appropriate method, is also a function of the cost of the overall construction project in relation to the cost of the method of improvement and reinforcement of the soil.
ii. The use of gravel piles will greatly increase the degree of consolidation and the safety factors of the final construction and final consolidation.
iii. There are many methods of improving seismically hazardous soils, but the most commonly used ones are compaction, stabilization and drainage methods. More precisely: all the above methods are used in non-coherent soils (sands, silts, gravels or mixtures), while stabilizing and compacting via gravel piles are used are used in cohesive soils (soft clays, organics).
iv. The probability of landslides under the influence of earthquake inertia forces depends on the combination of seismic loading and the pre-existing geological conditions.
v. Landslides are a phenomenon bearing extensive social, environmental and economic consequences, since, apart from the financial burden due to the collapse of a technical work or of interruption of transportation it is often accompanied by the degradation of the natural environment and the loss of human lives.
vi. The antiseismic design of non-reinforced and reinforced slopes and embankments is a major issue at a global level, mainly due to the environmental and economic consequences of their failure.
vii. The environmental impact resulting from failures in slopes, trenches, embankments, and dams are primarily the following:
- Significant impact on factors and variables of the natural and man-made environment that lead to deforestation, desertification and extinction of biological species, as many endemic species are particularly sensitive to disturbance.
- Reduction of biodiversity due to the destruction of habitat.
- Water pollution and disturbances in the flow and natural environment of rivers in the event of failure of dam slopes.
- Air pollution, due to the continuous operation of machinery and trucks used for the removal of soil, and the remedying of failures resulting from landslides.
- The proposed safeguards that fall in the category of immediate rehabilitation and are considered mild intervention, regard retaining structures, extensive excavations and formation of new slopes with low gradients, using flights and vegetation cover.
- The biological engineering methods used both for the protection and stabilization of the slopes are absolutely environmentally friendly, limiting interference in environmentally sensitive areas.
- Alternative stabilization methods have positive effects on surface landslides and solid materials, while at the same time not creating further environmental problems.

In accordance with the opinion of the authors of this article, the burden of environmental protection must be shifted from rehabilitation, to the prevention of failures, so that the environmental impact assessment shall be made in advance, based on the environmental design of slopes and engineering in general.

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