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CASE HISTORIES OF DAMAGE OF FOUNDATIONS NEAR SLIDING SLOPES

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ABSTRACT

The paper studies the effect of large slope movements on foundations through case histories. More than 30 well-documented case histories of damaged buildings near the tip of slopes due to excessive movement caused by either heavy rain or earthquakes were collected. The case histories showed that a critical factor affecting the level of damage of buildings, is the coefficient I, that is defined as the ratio of the width below the foundation that settles by the total width of the foundation: (a) When $I<0.2$, collapse does not occur, even if settlement is very large, (b). When $0.2<I<1.0$, the level of damage depends both on settlement and the factor l. (c) When $I=1$, buildings may not collapse, even if the settlement is very large, about 1m, but damage and rotation may be high. The above hold regardless of the cause of the slide: heavy rain or earthquake.

INTRODUCTION

Buildings are sometimes built near the edge or on natural slopes. The panoramic view may be one reason. Due to heavy rain, or earthquake the slope may slide. The settlement induced by the slide may cause considerable damage, or even collapse of these buildings. On the other hand, seismic codes do not give values of tolerable ground displacements (e.g. European Prestandard, 1994). A methodology to propose tolerable ground displacement values for structures near or on slopes is to collect case histories of structures on or near slopes that suffered ground displacement and investigate its effect on buildings.

Towards this purpose, the paper collects and studies historic cases of damage of buildings due to slides of slopes. In particular, the paper studies the effect of slides at structures founded on the crest, or the upper top part of the slope. It does not study the effect of slides at structures near the toe of the slope. Furthermore, it studies only buildings with shallow foundations. Case studies were collected regardless the cause of slides and is then investigated if the cause of slides affects the relationship between slide movement and level of damage of the structure.

The paper, first in section 2 presents a collection of historic cases. All slides collected were caused by (i) earthquakes or (ii) heavy rain. Then, in section 3 it relates the level of damage of buildings with the ground displacement. The methodology used involves the following steps: (a) General description of the observed ground movement, (b) definition of levels of damage of buildings, (c) selection of critical parameters that describe the ground movement and affect the damage of buildings, based on (a) and (d) statistical analyses that relate the level of damage of buildings with the critical parameters that were selected in (c). Even though in most cases collected the geometry and characteristics of the slope are known, characteristics of the building and its foundation are not known. Thus, the analysis is not performed in terms of the type of structure.

HISTORIC CASES

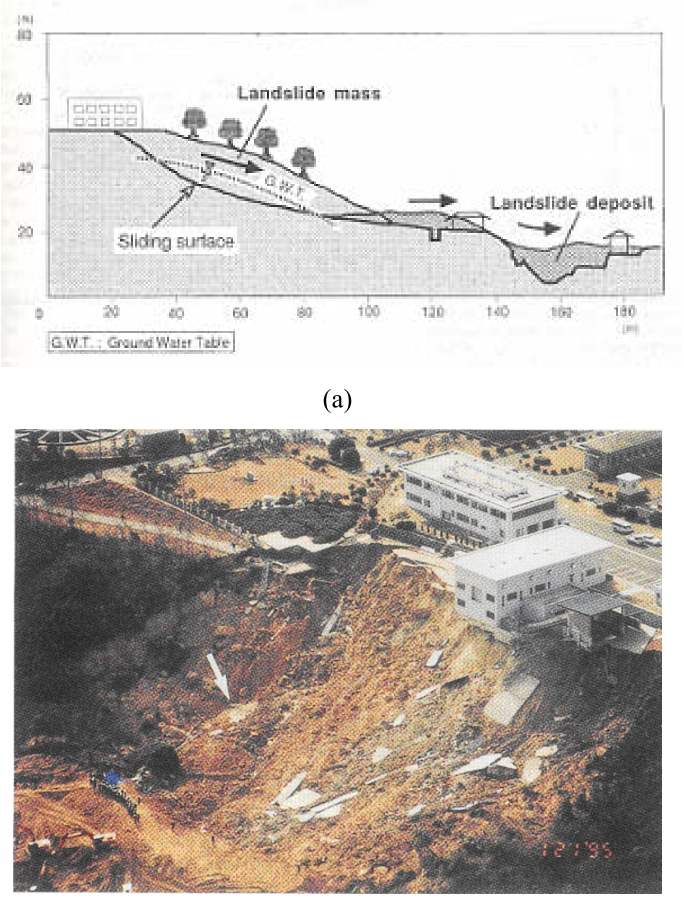
The landslide “Nikawa” due to the Hyogoken-Nambu (Japan) Earthquake

The slide was caused by the Hyogoken-Nambu (Japan) earthquake that occurred on 17/1/1995. It had JMA Magnitude 7.2, and focal depth 14 km. The slide occurred at distance 30-35 km, from the epicenter. Distance from the fault projection was 1 to 5 km. Estimated maximum horizontal acceleration was 0.35 to 0.60 g, where g is the acceleration of gravity.

Fig. 1a gives the cross-section of the Nikawa slide (Sassa at al, 1995, Sassa et al., 1996). The slide width was about 100m. The landslide volume was 110.000 to 120.000 m^3. Estimated displacements are 50 m. The slide was very rapid.

The region has two formations: the soil and the underlying rock at a depth of about 35m from the crest of the slope (Sassa at al, 1996). The water table level (measured about a month after the earthquake) is given in Fig. 1a. The soil formation was blue granitic sands including clays from the Osaka group. Geotechnical data of the soil formation includes cyclic ring shear tests. Sassa et al. (1996) performed two fast cyclic ring shear tests on samples with a degree of saturation of 0.35, to simulate average field conditions. They illustrate that as a result of cyclic loading, the sand resistance first increases and then drastically decreases. The peak total friction angle is about 28° and the residual total friction angle is only 8.5°. The residual strength value occurs at very large shear displacement, about 25m. Yet, at 1m displacement most of the soil strength has already been lost. This small value of residual friction angle explains the rapid occurrence of the slide. Grain size distribution analyses illustrated that before the shearing the percent of fines was about 0, while after shearing due to grain crushing it increased to about 15 and 30% for confining stresses 100 and 300kPa respectively.

With a landslide volume in the order of 110,000 m^3, moving rapidly over a distance of about 100 m, the slide destroyed 11 residential buildings causing 34 fatalities (Sassa et al., 1996). It is of interest to observe that a building at the top and near the edge of the slope did not collapse (Fig. 1b), presumably because (a) the foundation of the building was rigid and (b) the width of the slide below the building was small (about 5m) compared to the width of the building (about 20m).



(a)

(b)

Fig. 1. (a) Cross-section and (b) figure showing the damage of a building n of the Nikawa slide (Sassa at al, 1996).

Damage in buildings in natural and man-made slopes as a result of the Northidge (USA) earthquake

The slides were caused by the Northidge (USA) earthquake that occurred on 17/1/1994 and had Moment Magnitude 6.7 and focal depth 18.5km.

Table 1 gives the cases of natural and man-made slopes considered by Stewart et al. (1995). The slopes were 10km from the epicenter, and less than 30km from the fault projection. The slopes had inclination that ranged from 20 to 30° and height that ranged from 3 to 26m. The fill material had thickness from 3 to 26m. The fill material was sandy without plasticity. The natural soil below was also sandy without plasticity. More details are given in table 1.

Table 1 gives the ground settlements in all cases. It can be observed that relatively small ground settlements (0.1-0.01m) occurred. A schematic illustration of ground displacement is given in Fig. 2a.

Stewart et al. (1995) studied structures that were damaged as a result of the above settlements. A schematic diagram and typical photo of building damage are given in Fig. 2. It can be observed that settlement extended about 10m from the edge of the slope and affected about 60% of the width of the houses. As a result of the settlement of the fill, the foundation slab collapsed and moved towards the slope. Table 1 gives characteristics of the damage of the houses in terms of the settlement. Characteristics of the houses are not given. It is believed that the buildings did not have rigid foundation.

Building at at the top of a hill that slid in the region of Pacific Palisades – Santa Monica, California as a result of the Northridge (USA), 1994 earthquake.

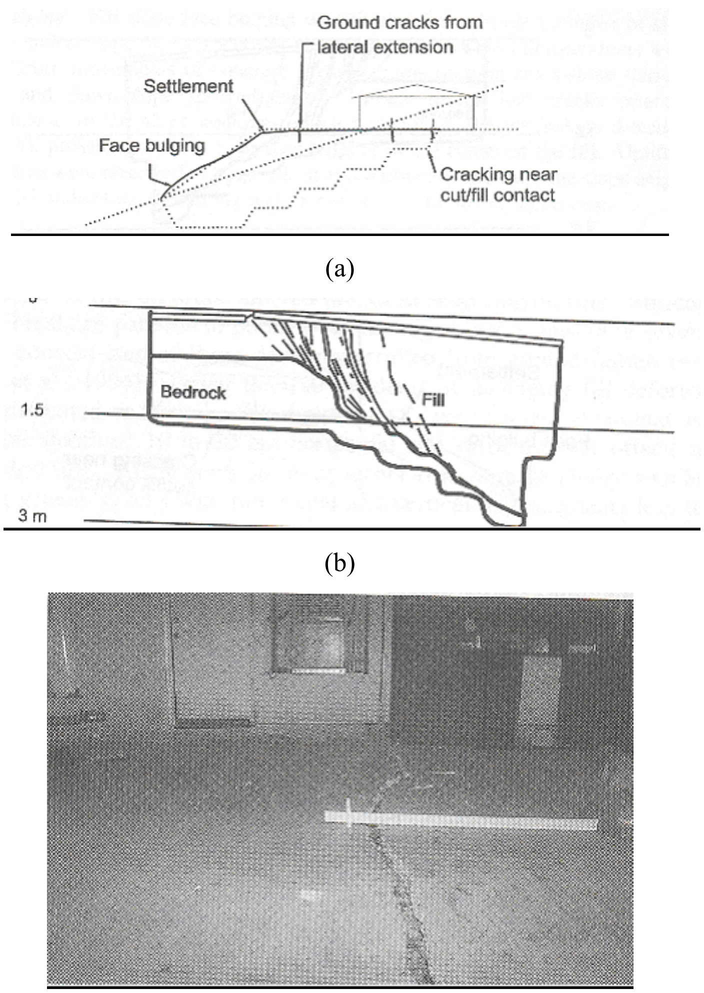
The slide was triggered by the Northridge (USA), earthquake, described in section 2.2. The slide occurred 35km from the epicenter.

The hill under consideration has side slopes of about 35° and height 20-25m. The top of the hill is smoothened by man in order to build the house. The hill is unstable and slides primarily as a result of heavy rainfalls and earthquakes. The hill is near the Pacific Ocean and thus the water table is approximately at the toe of the slope (http://pubs.usgs.gov/of/1996/ofr-96-0263, 2006)

The hill under consideration is part of the hills and mountains near and parallel to the Pacific Ocean, located South-West of the San Andreas – California fault. The mountains and hills were formed by faults in direction from North-West to South-East due to convergence of plates of the lithosphere. The prevailing geologic formation Topanga exists in the region. It consists of sands, silts and low plasticity clays (http://pubs.usgs.gov/of/ 1996/ofr-96-0263, 2006) .

The slide was shallow (Fig. 3) having 2-5m depth. It occurred in heterogeneous soil consisting mainly of sands and silts with small cohesion. Estimated slide displacement is 7m.

The slide caused partial collapse of a house very near the edge of the slope (Fig 3). The house was wooden and had one floor. The house partly collapsed, presumably because the foundation slab failed. The width of the foundation that was affected by the slide was about 3m out of the about 10m of the total width.



(a)

(b)

(c)

Fig. 2. Damage of buildings as a result of the Northidge (USA) earthquake: (a) and (b) chematic illustration and (c) typical photograph of the ground displacement and damage of buildings (Stewart et al., 1995).

Table 1. Cases of damage in buildings in man-made slopes as a result of the earthquake of Northidge, 1994 in USA. The settlement (ρ), the factor I (defined as the ratio of the width below the foundation that settles by the total width of the foundation) and the level of damage factor (L - see table 2) and are also given (modified from Stewart et al., 1995).

No	Fill type	Inclin. (H/V)	Height (m)	ρ (cm)	I	L
N1	CL/ML			13	0.6	2
N2	SM	1.5-2:1	23	15	0.6	1
N3	SC/CL	-	5.2	8	0.6	1
N4		1.5:1	3.6-4.5	13	0.6	1
N5	SC/CL	2-3:1		8	0.6	1
N6	SC/ML	1.5:1	3-6	6	0.6	1
N7	ML			8	0.6	1
N8	SM/SC	1.5:1	26	10	0.6	2
N9	SC	1.5:1	24	4	0.6	1
N10	CL		2.5-3	5	0.6	1
N11	SM		9	11	0.6	1
N12	SM	2:1	13.5	4	0.6	2
N13	SC	2:1	7.5	9	0.6	1
N14	SC/GC			6	0.6	1
N15	sand w/ gr.	2:1	9-11	10	0.6	1
N16	SM			8	0.6	1
N17	SM	2:1	9.6	18	0.6	1
N18	SM	2:1	2.4-3	4	0.6	1
N19	SM	1.5:1	2.1	9	0.6	1
N21	Sand	2:1	3.6	9	0.6	1
N22	SC	1.5:1	15	9	0.6	1
N23	SM/SC	1.5:1	5.4	6	0.6	1
N24	-	1.5:1	15	7	0.6	1
N25	SM/ML	1.5:1	15	4	0.6	1
N26	SM/ML	1.5-2:1	7.5	4	0.6	1
N27	CL/SC	-		8	0.6	1

Fig. 3. Photograph of a house that was destroyed as a result of a slide at Pacific Palisades, by the Northidge, 1994, earthquake. (http://pubs.usgs.gov/of/1996/ofr-96-0263, 2006)

Effect of the 4th Avenue Anchorage slide of the Alaska, 1964, earthquake

The slide was triggered by the Alaska, earthquake that occurred on 27/3/1964 and had Surface Magnitude 8.5. The slide occurred about 130km from the epicenter. Estimated peak acceleration is 0.15-0.20 g and duration of shaking was four to seven minutes, with potentially damaging shaking lasting approximately two to three minutes (Stark et al., 1998).

Fig. 4 gives a cross-section of the slide (Stark et al., 1998). The landslide mehanism was horizontal translation characterized by graben development. Slide horizontal translation was about 5m. Graben inclination is about 40^o.

The cause of failure appears to be the undrained failure of the soft sensitive "bootlegger cove clay" at depth of about 15m. This formation is a slightly overconsolidated sensitive clay (The overconsolidation ratio, or OCR, is around 1.2). The plasticity index is between 7 and 22 and the plastic limit is between 20 and 30. Constant volume ring shear tests showed that peak shear strength is reached after 1-2 mm of displacement. Fully reduced undrained residual strength is reached at a displacement of 80-100 mm. The final undrained residual strength ratio (S_u/σ'_o) is approximately 0.06, whereas the undrained peak strength ratio ranges between 0.17 and 0.23 (Stark et al., 1998). The small residual strength of the clay and the large intensity of the earthquake explain the triggering of the slide.

As illustrated in Fig 4, the large seismic displacement caused large settlement and rotation of a building, that made it uninhabitable. Yet, the buildings did not collapse.

School building that was destroyed as a result of a slide at Government Hill, at Anchorage, during the Alaska earthquake of 1964

The slide at Government Hill was triggered by the Alaska 1964 earthquake, described in the previous section. The slide occurred about 130km from the epicenter.

Soil conditions at the Government Hill slope are similar to those described in the previous section. The cause of failure appears to be the undrained failure of the soft sensitive bootlegger cove clay, described in the previous section. Both the horizontal displacement and the settlement in the vicinity of the slide are about 5m (Fig. 5).

A school was located near the slope that slid (Bolt, 1978). As illustrated in Fig. 4, about 8m of a 20m wide school was in the air, without foundation soil below it, as a result of the slide. The building partially collapsed, presumably because the foundation was not rigid enough.

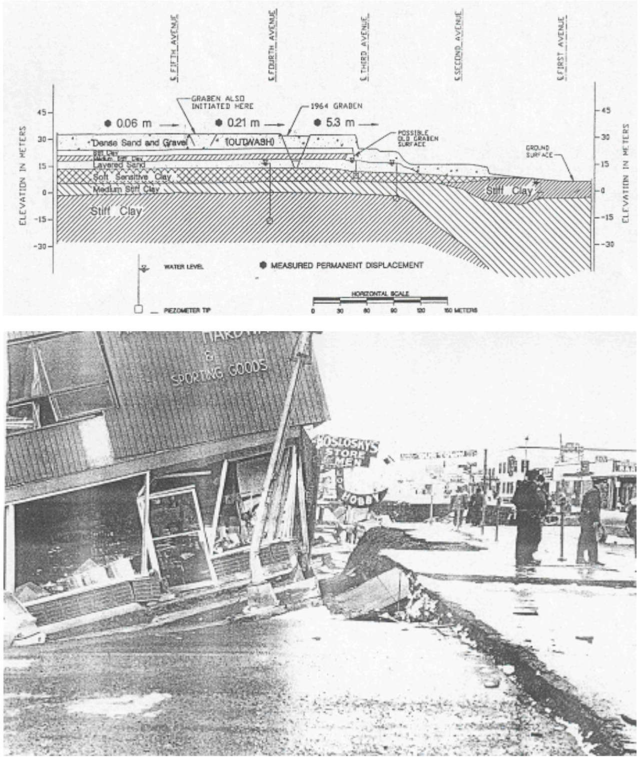


Fig. 4. Cross-section and figure showing the damage of the a building near the edge of the slope of the 4th Avenue Anchorage slide of the Alaska, 1964, earthquake. (Stark et al., 1998, Bolt, 1978).

Fig. 5. School building that collapsed as a result of a landslide at Government Hill, Anchorage, as a result of the Alaska, 1964 earthquake (Bolt, 1978).

Houses that suffered settlement and rotation as a result of the slide at Turnagain Heights at Anchorage during the Alaska earthquake of 1964

The slide at Turnagain Heights was triggered by the Alaska 1964 earthquake, described in section 2.4. The slide occurred about 130km from the epicenter.

A cross-section of the slope is given in Fig. 6a. The slope had inclination about 20^{o}. The nothern portion of Achorage is built on a sand and gravel outwash deposit overlying a thick stratum of bootlegger cove clay. The upper and lower zones of this clay deposit are fairly stiff and competent, but the central portion is weak and sensitive. This portion lost its strength and this caused the slide.

The Turnagain slide was the largest of five major slides in Anchorage extending about 2500 meters along the shore line (Bolt, 1978, Van Rose, 1983, Mobley , 1995). The maximum retreat inland was about 180m and the toe of the slide extended about 200m into the inlet. It was estimated from personal accounts that the slide began moving after about two minutes of intense motion. The slide progressed inland with time.

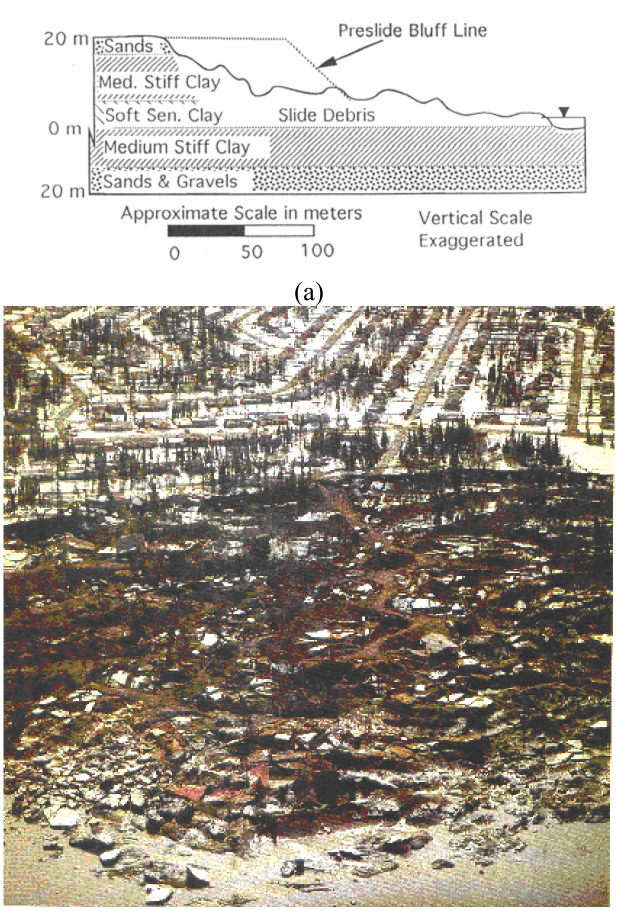
The houses on the slope moved downwards many centimeters or meters (Figs. 6b, 7a, 7b). The houses were wooden, one-story and two-story, with rigid foundation. The houses in the upper part of the slope moved horizontally less than 2m and did not collapse. The houses in the lower part of the slope moved more (about 10 to 120m) and some of them practically collapsed

<u>House that was damaged as a result of a slide caused by heavy rain in 2003 near Chora in Skyros, Greece</u>

The slide was caused by heavy prolonged rain that occurred in the winter of 2003 in the island of Skyros (one of the Sporades, in the Aegean Sea) in Greece.

The slope that slid has height about 30m from the sea level, inclination about 40^{o} and its toe is in the sea (Figs. 8a, 8b). Laboratory tests on the laboratory of the author revealed that the soil of the slope is a low-plasticity clay (classified as CL) with Liquid Limit 37%, Plastic Limit 23%, Plasticity Index 14% and percent of fines 57%. The slope slid by 5m at a region of about 30m. The slide had considerable depth, about 5m.

A two-floor building was on the slope. The building, of reinforced concrete, was recently constructed. The building was constructed by excavating the side of the hill and constructing a side retaining wall. As a result of the slide, the building was separated from a wall by settling by about 1.5m and rotating by about 15^{o} (Figs. 8a, 8b, 8c). The wall practically did not move (Fig. 9a). Even though the displacement and rotation of the building was considerable, the building did not collapse. Yet, it suffered severe cracks and wall movements (Fig. 9b).



(a)

(b)

Fig. 6. The slide at Turnagain Heights as a result of the the Alaska earthquake of 1964. (a) cross-section of the slide, (b) photo of the slide.

<u>Structure on slide as a result of heavy rain in 2003 at Kastro, Sifnos</u>

The slide was caused by heavy prolonged rain that started on 16 February 2003 in the island of Sifnos (one of the Cyclades, in the Aegean Sea) in Greece and lasted for 36 hours. Inhabitants say that they have not experienced such rain intensity for at least 50 years (Stamatopoulos A. and Stamatopoulos C., 2003).

The slope under consideration has height about 30m, inclination about 30^{o} and its toe is in the sea. It consists of sand, and includes silt, cobbles and small rocks. Grain size distribution tests indicated sand with 15% fines without plasticity. The specific gravity of the soil grains was found 2.81 and the maximum and minimum densities are 1.90 and 1.26 t/m^{3} respectively. Triaxial tests performed in the laboratory of the author gave under drained conditions $c = 0$, $\varphi = 31^{o}$ and under undrained conditions total strength values $c = 9$kPa, $\varphi = 21^{o}$ (Stamatopoulos C. and Stamatopoulos A. , 2005).

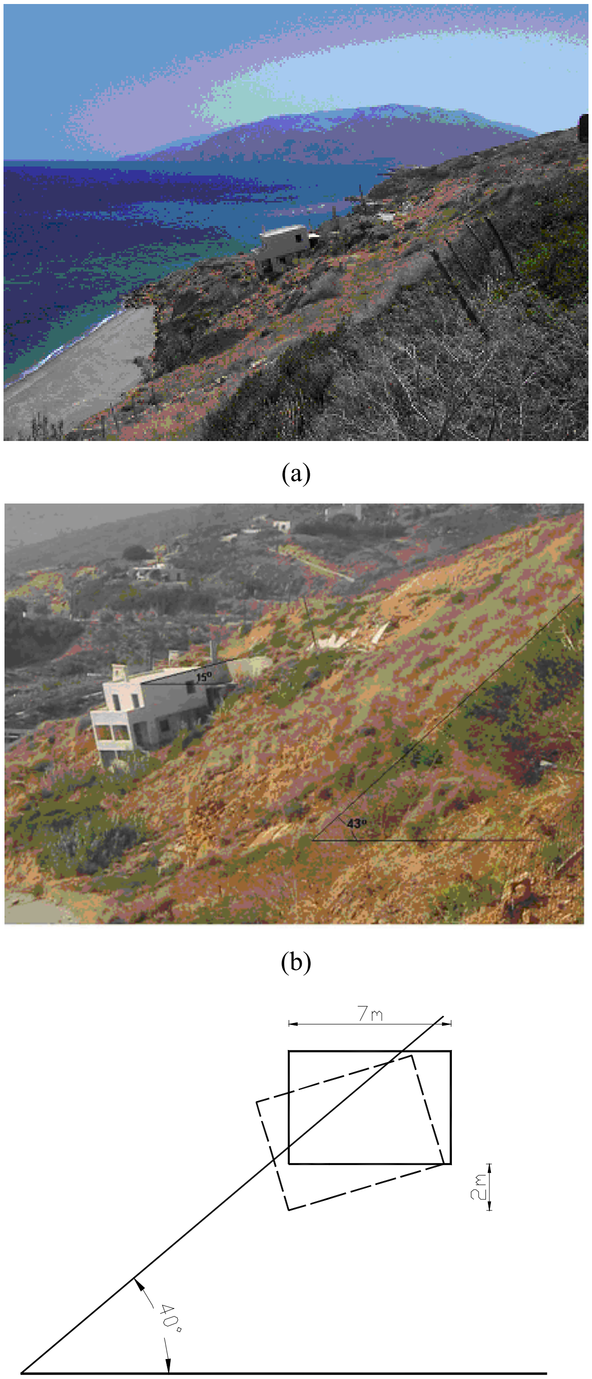
The sliding surface was approximately parallel to the slope and at a small depth from the surface, about 2 m. Ground displacement was about 5m (Fig. 10a).

A two-storey small house was near the edge of the slope. The building was recently constructed, of reinforced concrete. As illustrated schematically in Fig. 10b, the sea side of the structure formed a veranda slab that was left in the air for about 1m. The width of the building is about 10m and of the veranda is about 3m. The small loads in the veranda slab that was left "in the air", as well as the strength of the concrete may explain why the slab was not destroyed as a result of the "undercutting" of the soil.

(a)

(b)

Fig. 7. The slide at Tanagain Heights as a result of the the Alaska earthquake of 1964. (a) schematic illustration of damage to buildings and (b) photos of damage to buildings (Bolt, 1978).

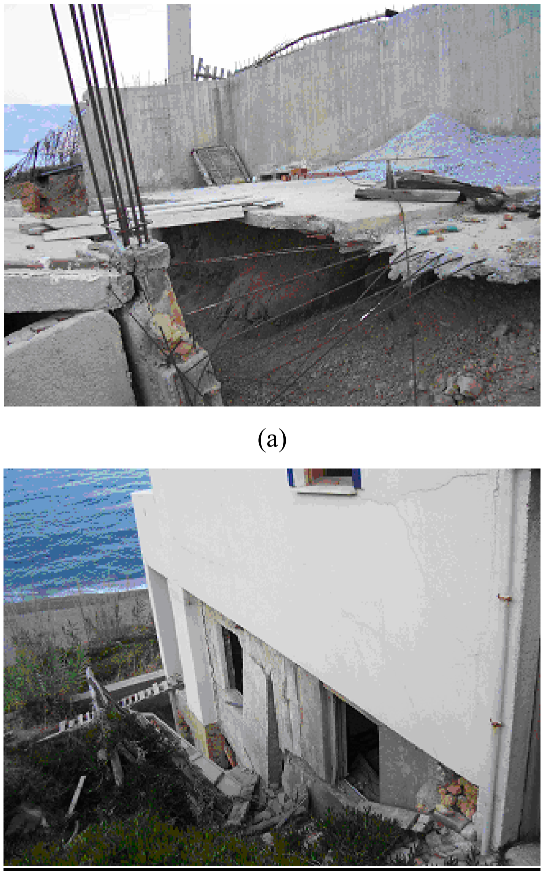


(a)

(b)

(c)

Fig. 8. Slide as a result of heavy rain in 2003 near Chora in Skyros: (a) the slide, (b) the rotation of the building, (c) Schematic diagram of the effect of the slide on the building (Stamatopoulos C. and Stamatopoulos A., 2005).


(a)

(b)

Fig. 9. Slide as a result of heavy rain in 2003 near Chora in Skyros: (a) separation of the building from the lateral wall and (b) damage of the building.

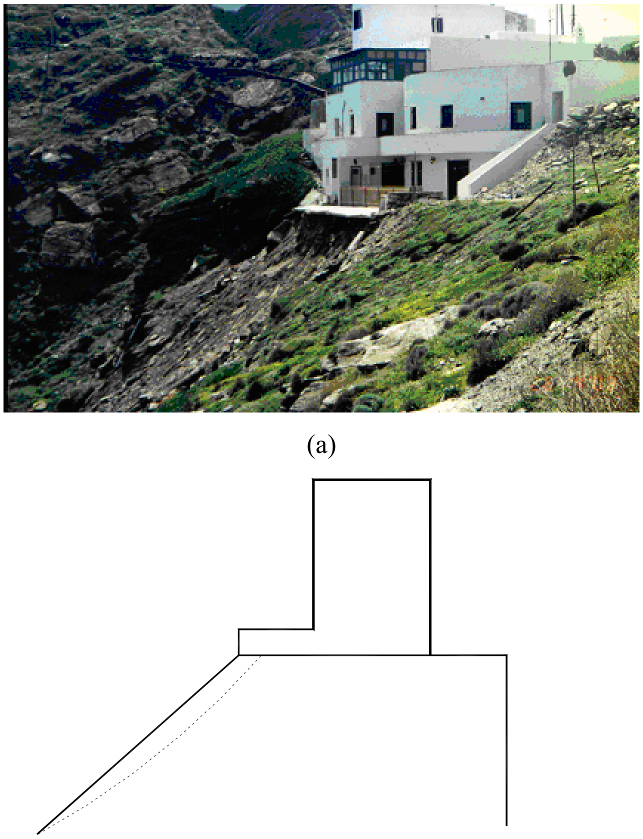
Structures on slide as a result of heavy rain in 1956 at Pacific Palisades – Potrero Canyon - De Pauw Street, California

The slide was caused by heavy prolonged rain that occurred in the winter of 1956 at Pacific Palisades, Potrero Canyon, California.

The slope angle is about 40^o (Fig. 11). The hill is near the Pacific Ocean and thus the water table is approximately at the toe of the slope. The geological conditions of the region of the slope are described in section 2.3. The hill is unstable and slides primarily as a result of heavy rainfalls and earthquakes

The slide was shallow. It had a depth of 3 - 5m. Ground displacement was about 7m (Fig. 11).

A two-storey building was at the surface, near the edge of the slope. As illustrated in Fig. 11, the edge of the building, over about 3m, out of total width of 15m, was left "in the air". The building did not collapse and was not severely damaged.


(a)

(b)

Fig. 10. Structure on slide as a result of heavy rain in 2003 at Kastro, Sifnos (a) Photo (Stamatopoulos and Stamatopoulos, 2003) and (b) Schematic diagram of the effect of the slide on the building.

Furthermore, a one-storey building was at the surface, near the edge of the slope. As illustrated in Fig. 11, the edge of the building, over about 1.5m, out of the total width of about 8m, after the slide was left "in the air". The building did not collapse and was not severely damaged.

Structure on slide as a result of heavy rain in 1969 at Palisades - Potrero Canyon - Friends Street, California

The slide was caused by heavy prolonged rain that occurred in the winter of 1969.

The slope angle was about 40^o (Fig. 12) The hill is near the Pacific Ocean and thus the water table is approximately at the toe of the slope. The geological conditions of the region are described in section 2.3. The hill is unstable and slides primarily as a result of heavy rainfalls and earthquakes

The slide was shallow. It had a depth of 3 - 5m. Ground displacement was about 6m (Fig. 12).

A one-storey building was at the surface, near the edge of the slope that slid. As illustrated in Fig. 12, the edge of the building, over about 1m, out of the total width of about 5m, was left "in the air". The building did not collapse and was not severely damaged.

(a)

(b)

Fig. 11. Structures affected from a slide as a result of heavy rain in 1956 at Pacific Palisades –Potrero Canyon - De Pauw Street, California (http:// geology.wr.usgs.gov/wgmt/elnino/scampen/examples.htm, 2006, http://www.gliff.org/usgs/listing/8692, 2006).

Table 2. Categories of level of damage (L) of structures

L	Description
1	Limited damage or damage that can be repaired easily (e.g. cracks) that do not pause any problem in the use or the stability of the structure
2	Damage that makes problematic and perhaps dangerous the use of the structure. Yet, damage repair is economically feasible
3	Severe damage that makes it impossible to use the structure. Repair of the structure is difficult and perhaps economically unfeasible.
4	Partial or total collapse of the structure with direct threat to human lives

Fig. 12. Structure affected by a slide as a result of heavy rain in 1969 at Palisades –Potrero Canyon - Friends Street, California (http:// geology.wr.usgs.gov/wgmt/elnino/ scampen/examples.html, 2006)

CORRELATION BETWEEN THE LEVEL OF DAMAGE AND THE SOIL DISPLACEMENT

General description of the response of the ground that was observed

The historic case studies collected above illustrate that the settlement of the crest of slopes is greatly non-linear: At the top of the slopes and near the edge, the soil slides downwards, possibly more than one meter, while at some distance from the edge of the slope, ranging from a few centimeters to about 20m, the soil does not move. This is the case for both earthquake-induced slides (Figs. 1, 3) and slides induced by heavy rain (Figs 9, 10, 11, 12). These are characteristics of shallow slides. An exception are the deep slides that were recorded at Anchorage as a result of the Alaska, 1964 earthquake. It is believed that these deep slides were a result of the particular geotechnical profile of the region, that has a liquefiable layer at some depth.

The historic case studies also illustrated that the soil mass adjacent to the slope moves downslope usually with displacement that decreases as the distance from the free side of the slope increases (Fig. 6b). Yet, often the displacement is random, as a result of many small failures and slides (Fig. 7a, Fig. 7b).

Levels of damage of buildings.

As a result of the displacements described above, structures are damaged. Four levels of damage of structures are defined, given in table 2. They include all possible levels of damage as a result of ground displacement.

Critical parameters

Critical parameters are needed to correlate ground deformation to damage to structures.

As a result of the highly nonlinear distribution of settlement near the edge of slopes described above, the cases that were collected above illustrated that a critical factor for the response is the coefficient I, defined as

$$I = B\rho / B \qquad (1)$$

where Bρ is the width of the region below the foundation that settles and B is the width of the foundation.

A small value of the coefficient I corresponds to buildings at the edge of slopes where the width of the slide is small compared to the width of the building. The factor I equals unity for buildings where settlement exists all over the width of the building.

In addition, a critical parameter is the maximum settlement of the soil below the structure. This parameter is used in building codes and rules (e.g. Lambe and Whitman (1969) to indicate maximum allowed or tolerated settlements.

The case histories illustrated that buildings with a value of the coefficient I equal to unity, usually rotate or are displaced horizontally (Figs. 4, 7, 8). The rotation of buildings generally increases as the settlement increases. The horizontal displacement also generally increases as settlement increases. Thus, as a first approximation, these two quantities are not considered additionally.

This work considers the response of buildings with shallow foundations. It is expected that, in addition to parameters related to ground displacement, given above, the damage of buildings depends on the type of shallow foundation. Buildings with rigid foundation should behave better than buildings with separate footings. It is believed that rigid foundations usually rotate, without damage in the structural integrity of the building. By contrast, in buildings on separate footings, even small settlement may cause structural damage, or even collapse. Yet, unfortunately, in most cases that were collected the type of foundation is not known in detail. For this reason, in this work differentiation in terms of type of foundation will not be performed.

Statistical analyses

Tables 1 and 3 present the level of damage in terms of the critical parameters that were described above for all the historic cases that were collected. The results are presented graphically in Fig. 13. Damage level is given in terms of the factor I, the settlement, and the cause of slide (heavy rain or earthquake). Results are separated for factors I: (a) smaller than 0.2, (b) between 0.2 and 1 (actually according to the collected data between 0.25 and 0.6) and (c) equal to one.

It can be observed that the damage of buildings is different when the factor I takes different values:
- (a) When $I<0.2$, collapse does not occur, even if settlement is very large. Thus, in this case, the amount of settlement does not affect the danger of collapse. In particular, the part of the building far from the edge of the slope, where the soil does not move, remains unaffected by the slide. The part of the building above the soil that slid, remains unaffected and simply is in the "air". Yet, as part of the building is in the air after the slide, considerable work is needed to reuse the building. This may include soil placement below the foundation, or partial demolition of the building.
- (b). When $0.2<I<1.0$, the level of damage depends both on the ground settlement and the factor I. It is expected that it may depend on type of foundation also. For I factor less than 0.3, collapse may not occur, even if settlement is very large. This is the case when the foundation slab does not fail (or collapse). For $1>I>0.4$, damage level increases as settlement increases and total or partial collapse of the building occurs for large settlement.
- (c) When $I=1$, buildings may not collapse, even if the settlement is very large, about 1m. Yet, the buildings may suffer considerable damage and rotation. For settlement larger than about 1m, as a result of the excessive displacements and rotations, the buildings cannot be reused.

The above hold regardless of the cause of the slide: heavy rain or earthquake.

CONCLUSIONS

The paper studies the effect of large slope movements on foundations thru case histories. More than 30 well-documented case histories of damaged buildings near the tip of slopes due to excessive movement caused by either heavy rain or earthquakes were collected.

The historic case studies collected illustrate that the settlement of the crest of slopes is greatly non-linear: At the top of the slopes and near the edge, the soil slides downwards, possibly more than one meter, while at some distance from the edge of the slope, ranging from a few centimeters to about 20m, the soil does not move. This is the case for slides induced both by earthquakes and heavy rain.

Analysis of the case histories illustrated that the damage of buildings is different when the factor I, defined as the ratio of the width below the foundation that settles by the total width of the foundation, takes different values:
- (a) When $I<0.2$, collapse does not occur, even if settlement is very large. Yet, as part of the building is "in the air" after the slide, considerable work is needed to reuse the building.
- (b). When $0.2<I<1.0$, the level of damage depends both on settlement and the factor l. It is expected that it may also depend on the type of foundation. For I factor less than 0.3, collapse may not occur, even if settlement is very large. For $1>I>0.4$, damage level increases as settlement increases and

total or partial collapse of the building occurs for large settlement.

- (c) When I=1, buildings may not collapse, even if the settlement is very large, about 1m. Yet, the buildings may suffer considerable damage and rotation.

The above hold regardless of the cause of the slide: heavy rain or earthquake.

Table 3. Level of damage (L) in terms of maximum ground settlement below the foundation (ρ) and the factor I for the historic cases that were collected. Remaining cases. The symbol (?) indicates not certainty.

No	Type of structure/ Found.	ρ (m)	Cause of slide	I	L
2.2.1/Nikawa	Rigid	30	Earth.	0.25	3
2.2.4/Santa Monika	Wooden/ ?	15	Earth.	0.3	4
2.3.1β/ Alaska-4st Ave	Concrete ?	1.5	Earth.	1	3
2.2.2/Alaska	Concrete ?	5	Earth.	0.40	4
2.3.2α/ Alaska-Turnagain Heights	Wooden/ ?	1	Earth.	1	3
2.3.2β/ Alaska-Turnagain Heights	Wooden/ ?	2.5	Earth.	1	3
2.3.2β/ Alaska-Turnagain Heights	Wooden/ ?	4	Earth.	1	4
2.3.2β/ Alaska-Turnagain Heights	Wooden/ ?	5	Earth.	1	4
2.3.4/Skyros	Reinf. concrete / Rigid	2	Rain	1	3
2.2.5/Sifnos	Reinforced concrete / Rigid	4	Rain	0.1	3
2.2.6-1/DePauw-California	Wooden?	7	Rain	0.2	3
2.2.6-2	Wooden?	5	Rain	0.2	3
2.2.7/Friends-California	Wooden?	6	Rain	0.2	3

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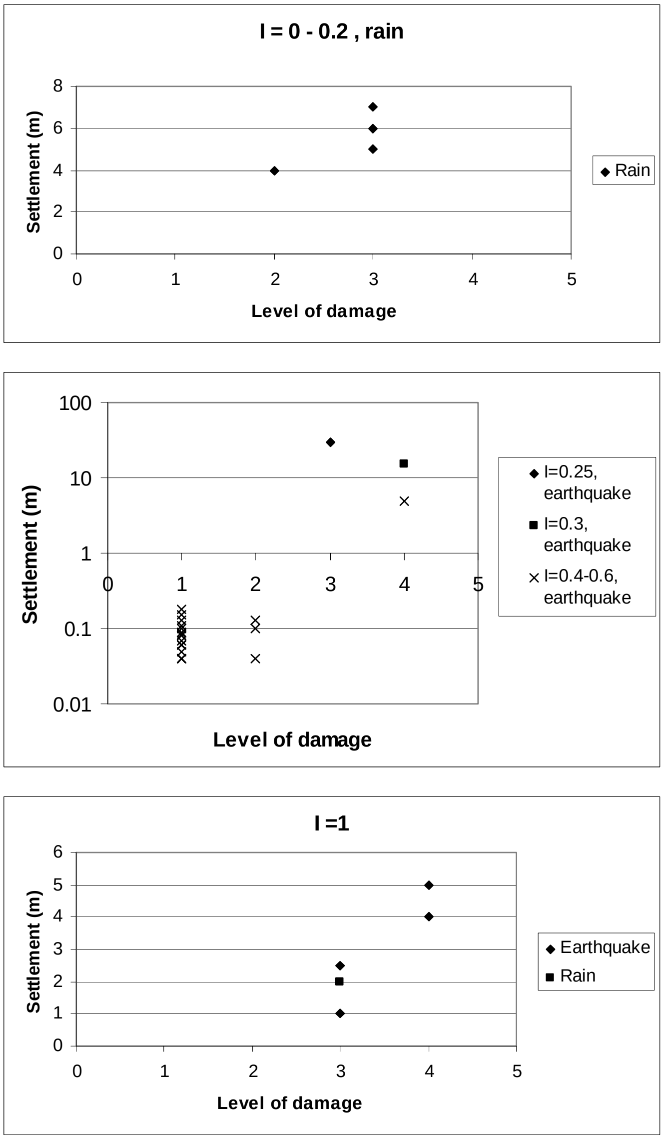

Fig. 13. Statistical analyses: Damage level in terms of the factor I, the settlement and the type of slide.

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