Liquefaction-induced ground deformations on a lake shore (Turkey) and empirical equations for their prediction

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Abstract: Liquefaction-induced ground deformation is a potential source of major damage to lifelines and structures during earthquakes. This type of permanent ground displacements caused substantial damage to buildings, lifelines and shores in the Eastern Marmara Region of Turkey during the devastating 1999 Kocaeli earthquake. One of the liquefaction-affected sites during this earthquake was Sapanca town located on the southern shore of Lake Sapanca. This study presents liquefaction assessments at Sapanca and multiple linear regression models for estimating the magnitude of liquefaction-induced ground displacement. After the earthquake field investigations both at Sapanca and along a zone on the shoreline, including in-situ tests and laboratory tests, were conducted. These tests along with measured displacement data, topographical data and an extended international database form the basis of this study. The assessments based on field performance data indicated that liquefaction at Sapanca has occurred within alluvial fan deposits at depths between 1 m and 14 m, and liquefaction and associated ground deformations mainly concentrated along the shore and creeks. For sites with no sand boils but with ground displacement greater than 1 m, thickness of the non-liquefiable layer was large. The models, which are based on data from Sapanca combined with a worldwide database, are suggested for predicting the liquefaction-induced ground deformations for free-face, sloping- ground and free face-sloping ground conditions. Statistical analyses revealed that the ground displacements estimated from the suggested empirical models show an agreement with the observed displacements and about 90% of the estimations fall into ± 20% of the scaled percent error.

R sume: La déformation au sol due au liquéfaction est une source potentielle de dommage majeur aux lignes de sauvetage et aux structures pendant les tremblements de terre. Ce type de déplacement permanent au sol a endommagé des bâtiments, des lignes de sauvetage et des rivages dans la région orientale de Marmara de la Turquie pendant le tremblement de terre très devastatrice de Kocaeli en 1999. L'un des emplacements affecté à cause du liquéfaction pendant le tremblement de terre était la ville de Sapanca située sur le rivage méridional du lac Sapanca. Cette étude présente des évaluations de liquéfaction à Sapanca et des modèles multiples de régression linéaire pour estimer l'importance de déplacement au sol due au liquéfaction. Les investigations sur le terrain à Sapanca et au long d'une zone sur le rivage, y compris les essais in-situ et les essais en laboratoire, ont été conduits. Ces essais avec des mesures de déplacement, des données topographiques et une base de données internationale approfondis forment la base de cette étude. Les évaluations basées sur des données d'exécution de terrain ont indiqué que la liquéfaction à Sapanca s'est produite dans des cones alluviaux profond de 1 à 14 m, et liquéfaction et déformations associées au sol sont principalement concentrées le long du rivage et des criques. Pour des emplacements sans des ébullitions de sable mais avec le déplacement au sol plus grand que1 m, l'épaisseur de la couche non-liquéfiable était grande. Les modèles, basés sur des données de Sapanca et combiné avec une base de donnée mondiale, sont suggérés pour prévoir les déformations au sol due au liquéfaction pour la surface libre, pour la surface incliné et pour les conditions de surface libre-surface incliné. Les analyses statistiques ont indiqué que les déplacements au sol estimés à partir des modèles empiriques suggérés montrent un accord avec les déplacements observés et environ 90% des évaluations tombent dans le ± 20% de l'erreur mesurée de pour cent.

Keywords: alluvium, earthquake, lateral spreading, liquefaction, penetration tests.

INTRODUCTION

The liquefaction-induced ground deformations resulting from earthquakes have been identified as a potential source of major damage to structures and lifelines. These permanent displacements cover areas as large as a few square kilometers and have amplitudes ranging from few centimeters to 5 m and more. They were numerous during the devastating 1999 Kocaeli earthquake of Turkey (M_w= 7.4) and caused substantial damage to structures and buried lifelines along the southern shoreline of Izmit Bay and Lake Sapanca, and in the city of Adapazari (Figure 1). Most detailed investigations on liquefaction phenomena were concentrated in the city of Adapazari (e.g. Bray *et al.*, 2001; Erken 2001; Yasuda *et al.*, 2001). The only investigation besides the authors' group (Aydan *et al.*, 2004) on the liqufaction-induced ground deformations at the southern shore of Lake Sapanca was carried out by Cetin *et al.* (2002) at a hotel area which is near to Sapanca town and covers an area of 0.33 km^2. Cetin *et al.* (2002) made a comparison between the lateral deformations and ground settlements observed at the hotel area, and those predicted from some existing empirical models. These investigators indicated that the methods employed under-estimated the settlement and over-estimated the observed lateral deformations.

This present study is intended to assess liquefaction and lateral spreading on the coast of Lake Sapanca, and to produce empirical models of liquefaction-induced ground displacement useful for predicting the magnitude of lateral spreading for free face, sloping ground and free face-sloping ground conditions. The permanent ground deformations were measured through the aerial photogrammetry technique developed by Hamada *et al*. (1986), and liquefaction susceptibility of the study site was investigated using the data from geotechnical boreholes drilled before the 1999 earthquake and during this study. Then, in addition to data obtained from the study site, an extended international database were employed for multiple linear regression analyses to develop empirical equations for predicting the magnitude of liquefaction-induced ground deformation which may be a valuable tool for practicing engineers.

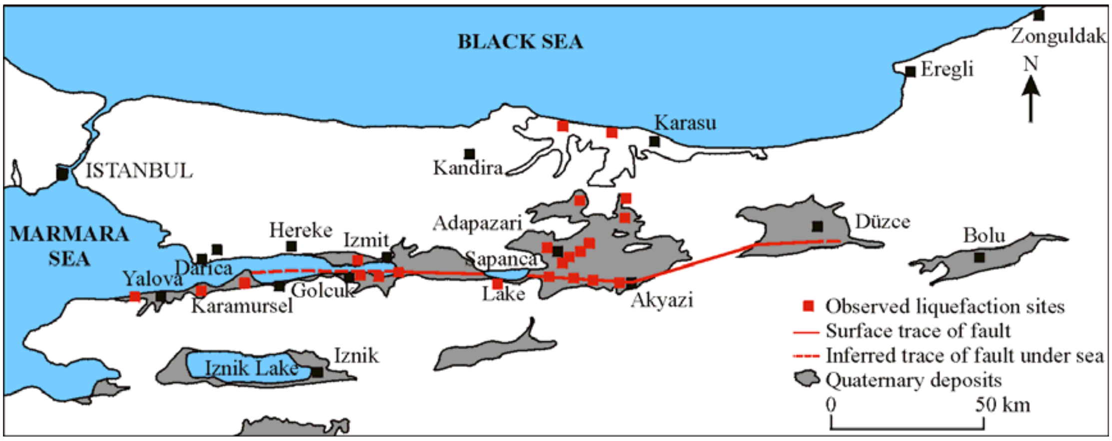

Figure 1. Liquefaction locations observed during the 1999 Kocaeli earthquake (after Aydan *et al*. 2000)

OBSERVED LIQUEFACTION-INDUCED DEFORMATIONS

Liquefaction-induced ground deformations caused extensive damage on the southern shore of Lake Sapanca where the incidents of sand volcanoes and sand blows were clearly visible at various locations. The general trends of the eruption fissures were systematically parallel to the shore with an orientation of N50°-75°W (Figure 2a). Sapanca Vakıf Hotel sank and moved towards the lake due to lateral spreading (Figure 2b). In addition, some holiday complexes, restaurants, parks and roads also moved towards the lake. Permanent displacements were measured from ground fissures and separated shifted walls on the shoreline (Figure 2c). Horizontal displacement due to lateral spreading occurred in the hotel area towards the lake was 352 cm, while it sank with its swimming pool about 0.3 m into the ground (Figure 2b). Displacements measured at neighboring residential houses and holiday complexes were between 2 and 3.05 m. No damage in the upper structures suggests that the ground may have moved to the lakeside and subsided during the earthquake due to lateral spreading. Towards the western part of the shore similar evidence of liquefaction-induced ground deformations such as sunken trees etc. were also observed. Based on the information from the Municipality of Sapanca (2003), liquefaction and associated ground deformations also occurred at the hotel site and its vicinity during the 1967 Mudurnu earthquake.

(a) (b) (c)

Figure 2. (a) Liquefaction fissure, (b) submerged hotel, (c) a damaged garden wall and ground fissure due to lateral spreading at Sapanca

GEOLOGICAL SETTING AND SEISMOTECTONICS

The study site is located in a ‘pull-apart’ basin extending between Sakarya River and Izmit Bay. Inclination of natural slopes ranges between 0.1 and 0.3%, and 2 and 4% at the western and southern parts of Lake Sapanca, respectively. Paleozoic metamorphic rocks, Late-Pliocene Karapürcek formation and Quaternary deposits are the geological units cropping out at the study site (Figure 3). Alluvial fans and recent alluvium with a thickness of reaching up to 100 m have been deposited along the southern shore of the lake.

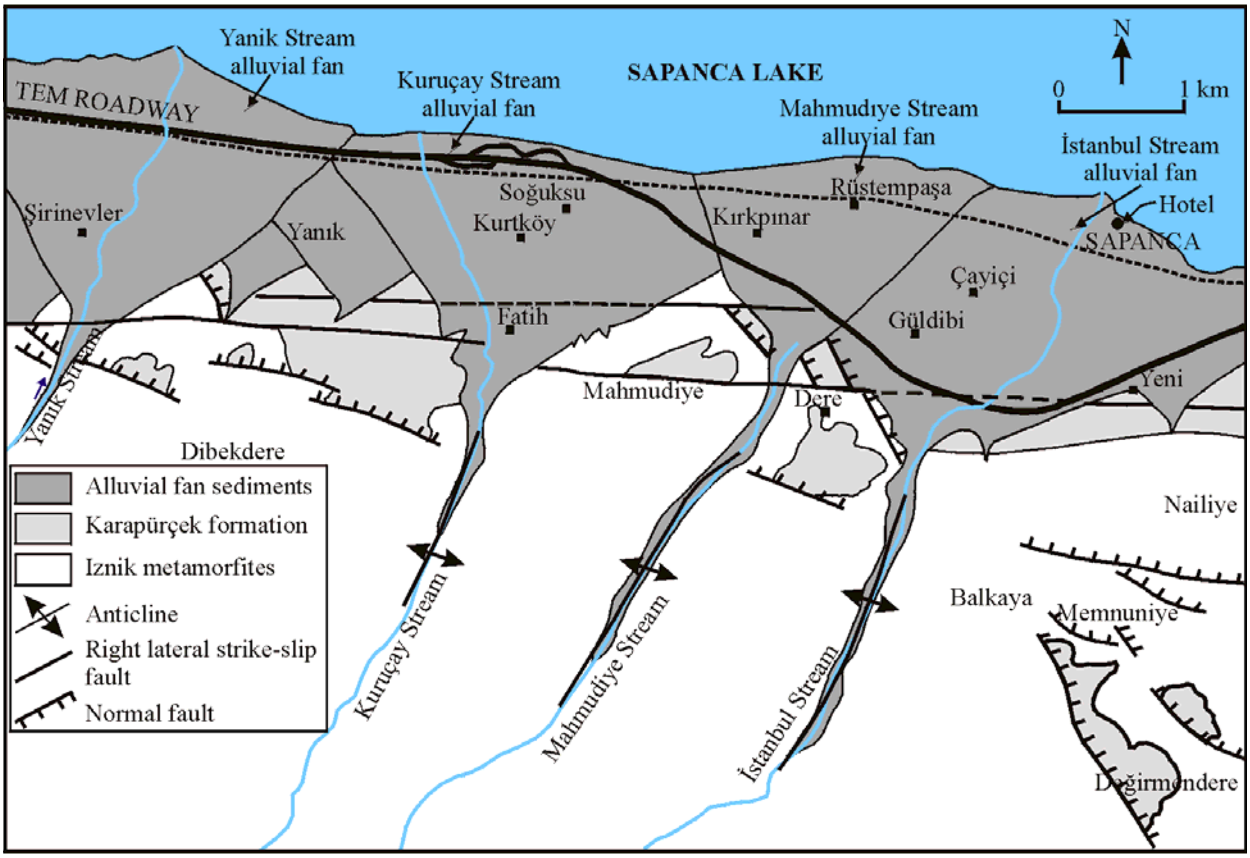

Figure 3. Geological map of Sapanca and its vicinity (after ODTU-MTA 1999)

Lake Sapanca is structurally controlled by the segments of the North Anatolian Fault Zone (NAFZ) and one of the products of pull-apart mechanism associated with the strike-slip motion of the NAFZ (Barka 1997). The focal plane solutions of the earthquakes occurring in the region indicated that the largest event took place by right lateral strike-slip faulting (Aydan *et al*., 2000). One of three areas regarded as seismic gaps (Ucer *et al*., 1997) is associated with the location of the Kocaeli earthquake. The southern part of the Sapanca-Gölcük segment of the NAFZ caused the Mudurnu earthquake of 1967 (M_w:=7.1) and resulted in loss of life and heavy damage in some settlements such as Adapazari, Akyazi and Sapanca.

MEASUREMENT OF GROUND DISPLACEMENTS

Measurement of the liquefaction-induced ground displacements in the study area was based on aerial photogrammetry technique proposed by Hamada *et al.* (1986) using both pre- (1994) and post-earthquake (1999) photographs by the General Command of Mapping of Turkey (Atak *et al*., 2004). For measurement points, manholes and tree roots were taken as points on the ground, while corner of roofs, bridges and poles were used as points off the ground. The three-dimensional coordinates of the common points on pre- and post-earthquake photographs were determined and their differences were interpreted as the liquefaction-induced displacements. The error in this method was estimated to be about 50-60 cm. The study site was subdivided into four sub-areas along the shoreline (Figure 4) and the ground displacements in these areas were taken as the observed displacement for the assessment of lateral spreading. Ground displacement vectors in one of the sub-areas are shown in Figure 5.

LIQUEFACTION ASSESSMENTS

Local Site Conditions

Local site conditions were evaluated based on data from boring, standard penetration tests (SPT) and laboratory soil classification tests. In addition to data from 55 previous boreholes drilled by Iller Bankasi (1991) and Cetin *et al.*

(2002), data from 14 new boreholes, which were drilled at locations with clear evidences of liquefaction during this study (Aydan *et al*. 2004), were also employed (Figure 4). In each new borehole, SPT was carried out at every 1 m interval and depth of the groundwater level was measured. Generally an artificial fill with a thickness of 0.5-1.5 m represents the surface layer, particularly near the shoreline. The soil conditions differ from east to west. While the ground mainly consists of sandy and gravely soils in the east (Areas 1 and 2 in Figure 4), the amount of fine grained soils increases in the west. Thickness of the silty sand layers range between 1 and 6.5 m, however it decreases away from the shoreline. Energy, borehole and overburden corrected SPT-N values, $(N_1)_{60}$, of these layers are generally between 3 and 30. An important portion of the samples falls into SM and SW-SP soil groups representing silty sands and poorly graded sands which are susceptible to liquefaction in terms of their grain sizes. Depth of the groundwater table is generally shallow and less than 2 m below the ground surface.

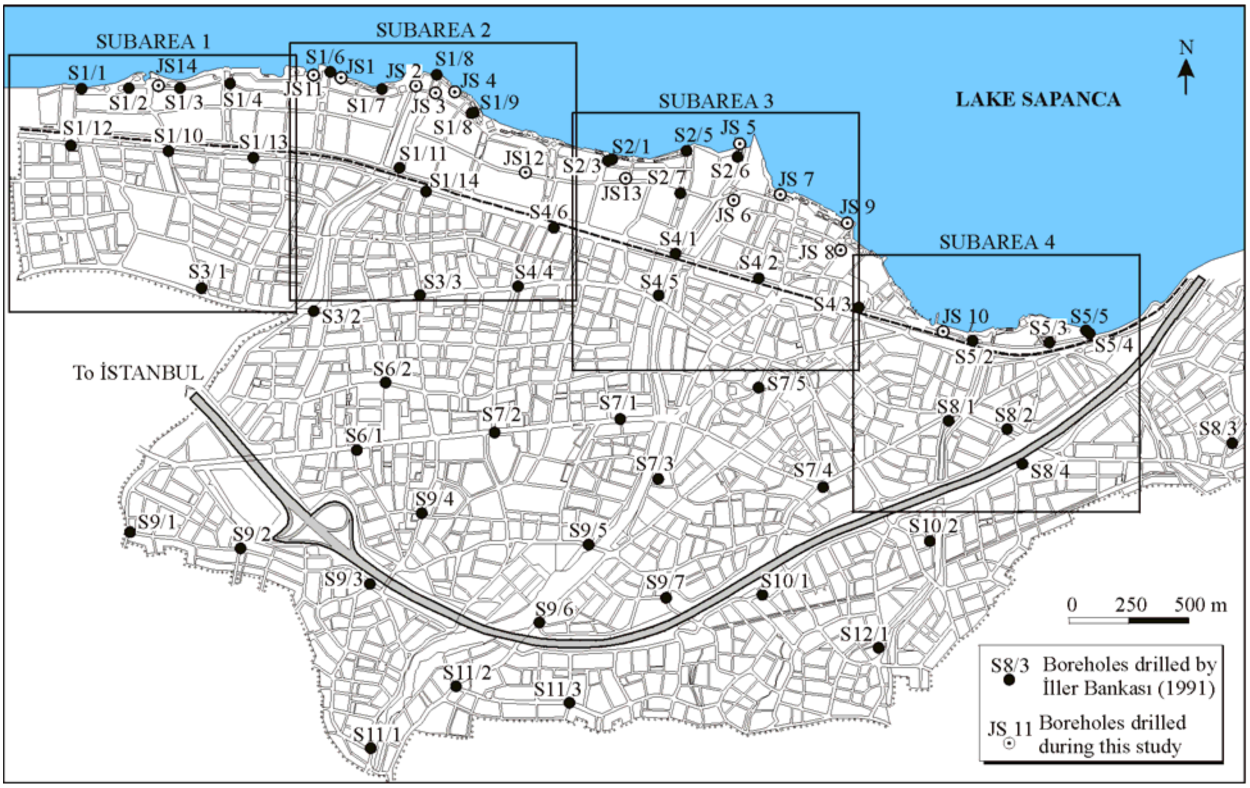

Figure 4. Locations of boreholes and sub-areas at Sapanca

Liquefaction Susceptibility Analyses

Liquefaction susceptibility analyses were carried out according to the method originally developed by Seed and Idriss (1971) and modified by Youd *et al*., (2001). The maximum horizontal ground acceleration was taken as 407 gal based on the analysis by Aydan *et al*. (2004) and the record of the Kocaeli earthquake from the nearby Sakarya strong motion station.

By considering the site observations and ground displacement vectors, layer thickness combinations of the liquefiable and non-liquefiable layers in the analyses were classified into four types (Figure 6). From Figure 6 it is evident that liquefaction at Sapanca during the Kocaeli earthquake appears to have occurred at depths between 1 and 14 m. The effect of the thickness of the non-liquefiable layer was also investigated using the Ishihara's empirical criterion (Ishihara 1985). Figure 7 suggests that liquefaction-induced ground disruption could be observed when the thicknesses of the liquefiable and non-liquefiable layers vary between 0.5 and 1.5 m, and 3.5 and 5.5 m, respectively. Two data points appearing below the boundary for 400 gal were obtained at locations where evident sand boils were not observed. While the data for types 1 and 3 both with lateral displacement greater than 1 m are above the boundary for 400 gal indicating that data plot in Figure 7 generally agrees with Ishihara's boundary.

EMPIRICAL MODELS FOR PREDICTING LATERAL SPREAD DISPLACEMENT

The method based on the sliding block analysis originally proposed by Newmark (1965) is used to estimate the rigid body motion of a liquefied layer through the consideration of input-waves and shear strength mobilized along the sliding plane (Dobry & Baziar 1992). The most difficult aspects in this method are how to select the residual shear strength properties and pore pressure variation during shaking and motion of the ground. With the increase of available data from earthquakes, a number of researchers have attempted to develop empirical models for predicting ground deformation, D_H. Hamada *et al.* (1986) proposed the first empirical models for predicting D_H on the basis of data from the 1964 Niigate earthquake of Japan. Their model has only two parameters, thickness of the liquefiable layer and the ground slope. Currently, most empirical models (Bartlett & Youd 1995; Bardet *et al*., 1999; Rausch & Martin 2000; Youd *et al*., 2002) consider seismological parameters, topographical factors and material property parameters. Kanibir (2003) compared the liquefaction induced ground deformations measured from aerial photographs of Sapanca and those predicted from the empirical models suggested by Hamada *et al.* (1986), Bardet *et al.* (1999) and Youd *et al.* (2002). About 70% of the ground deformations predicted from the free-face (FF) model of Bardet *et al.* (1999) fall into ± 20% of the scaled percent error indicating a better estimate when compared to those from other models for the studied case (Figure 8). Kanibir (2003) also indicated that the model by Hamada *et al.* (1986) ignores seismic and geotechnical parameters and that the grain sizes of sediments in the Sapanca area are generally coarser than those in the cases used by Hamada *et al.* (1986).

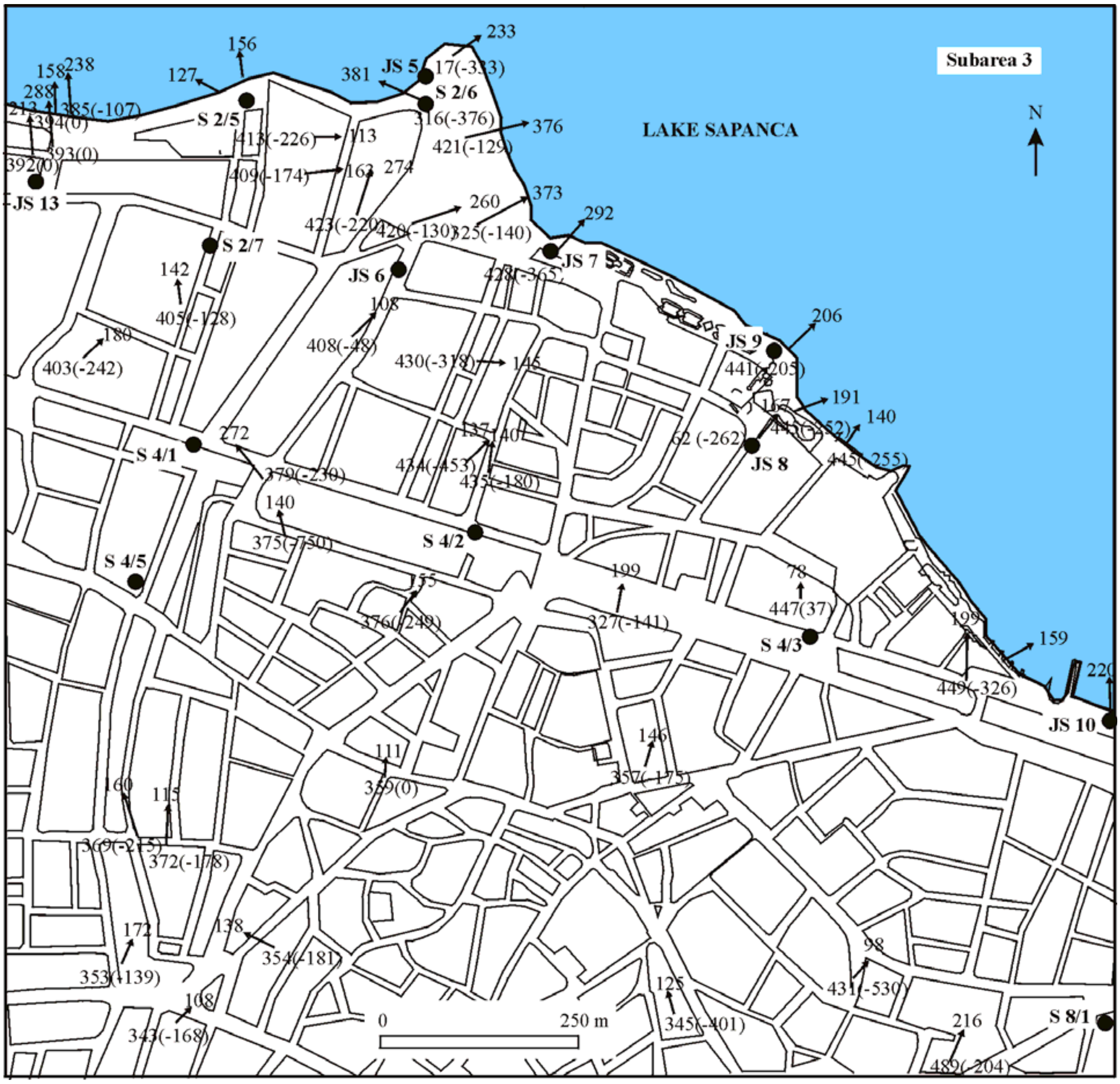

Figure 5. Ground displacement vectors in sub-area 3

This present study aims to develop empirical equations for a better prediction of lateral spread displacements incorporating the database from Sapanca and a world-wide database compiled by Dr. T.L. Youd of Brigham Young University, USA (http://www.et.byu.edu/ce/ceweb/faculty/youd/data.html), and then to test the predictive performance of the equations for the Sapanca case. For the Sapanca database, the ground displacements in sub-areas 1 to 4 and their locations with boreholes were considered. When the location of measurement point does not coincide with the borehole, the ground displacement of the nearest measurement point within the perimeter of 50 m of the borehole was taken as the displacement at the borehole location. With the addition of the Sapanca database, the combined world-wide database has 499 entries from different parts of the world. Among the recorded D_H values in the world-wide database over 60% of the data are from the 1964 Niigata earthquake. The data in both databases fall into four main categories such as measured ground displacement data, free-face and sloping-ground topographical data, seismic data and soil property data. As illustrated in Figure 9, free faces are abrupt variations of ground surface elevation such as quay walls and embankments. In some instances, the displacement of free faces appears to induce that of the liquefaction-induced ground deformation adjacent to it (Hamada & Wakamatsu, 1998). Sloping-ground (SG) cases correspond to free-field conditions far away from free faces. Because the topography at Sapanca is generally defined by a combination of sloping-ground and free-face, in addition to FF and SG conditions a complete case (free face – sloping ground; FFSG) was also considered in multiple regression analyses. For the Sapanca database, the horizontal distance from the lake shore to the borehole is taken as the distance to free face (L), and difference between crest and toe was assumed as the height of free face (H). The values of W were found from the cross-sections. Bartlett & Youd (1995) suggest that in the case of W<1%, ground slope condition generally controls the displacement behavior. While free-face failures were usually initiated at localities where 1%≤W≤5%. Thus for this range, it is difficult to judge whether free-face or sloping-ground condition prevails, and Bartlett & Youd (1995) suggest estimating D_H from both equations developed for FF and SG conditions, and applying the larger result for evaluation purposes. For 5%≤W≤20%, free-face condition generally controls the displacement behavior. The above mentioned criteria were considered for grouping the data for regression analyses. It is also noted that both W and S terms were used for FFSG case in regression analyses.

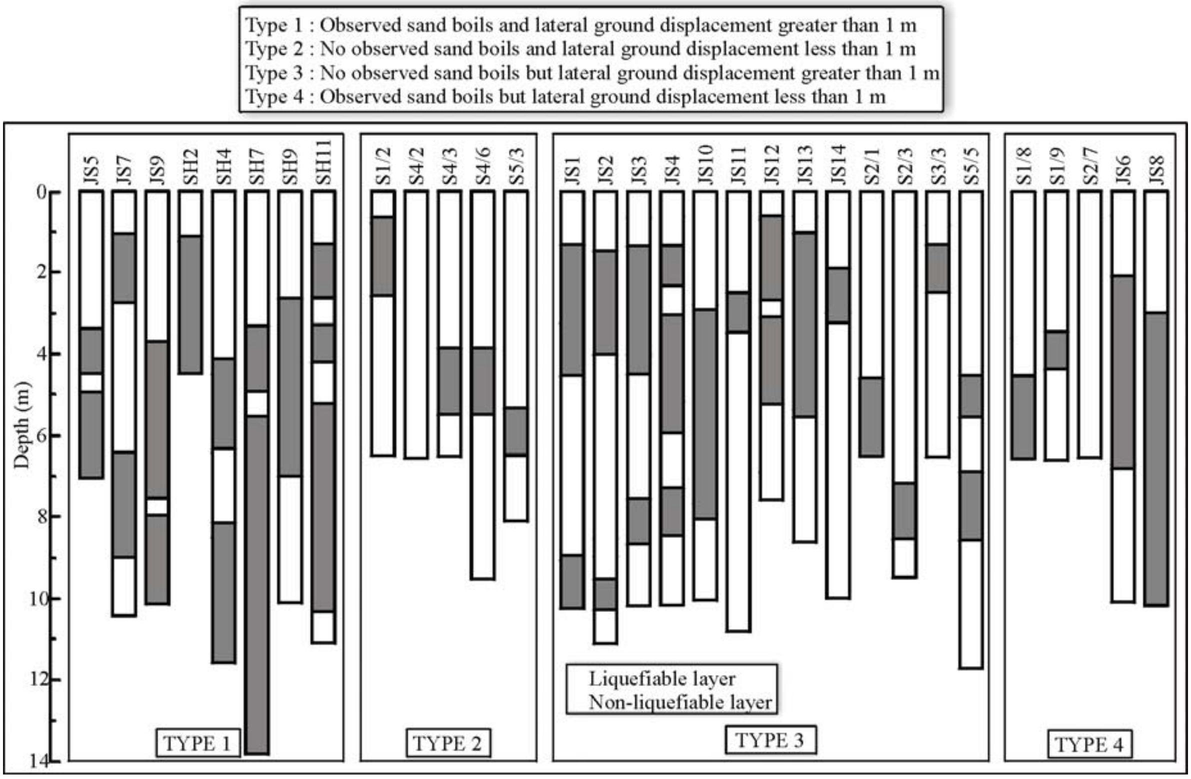

Figure 6. Estimated liquefied and non-liquefied layers in Sapanca

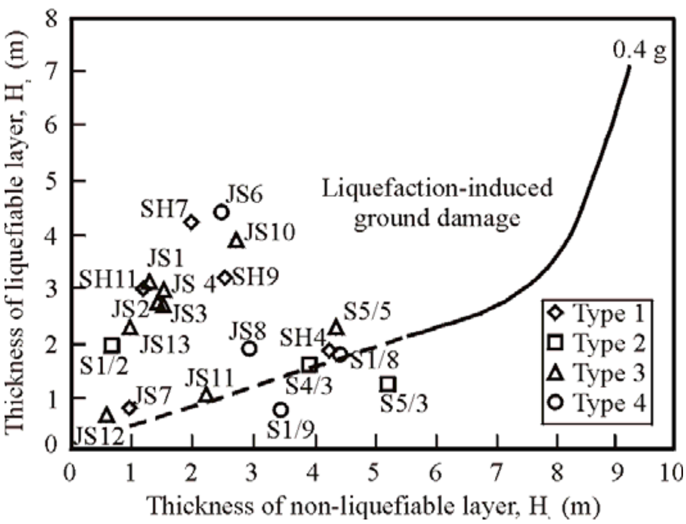

Figure 7. Relationship between the thickness of the liquefiable and non-liquefiable layers for Sapanca

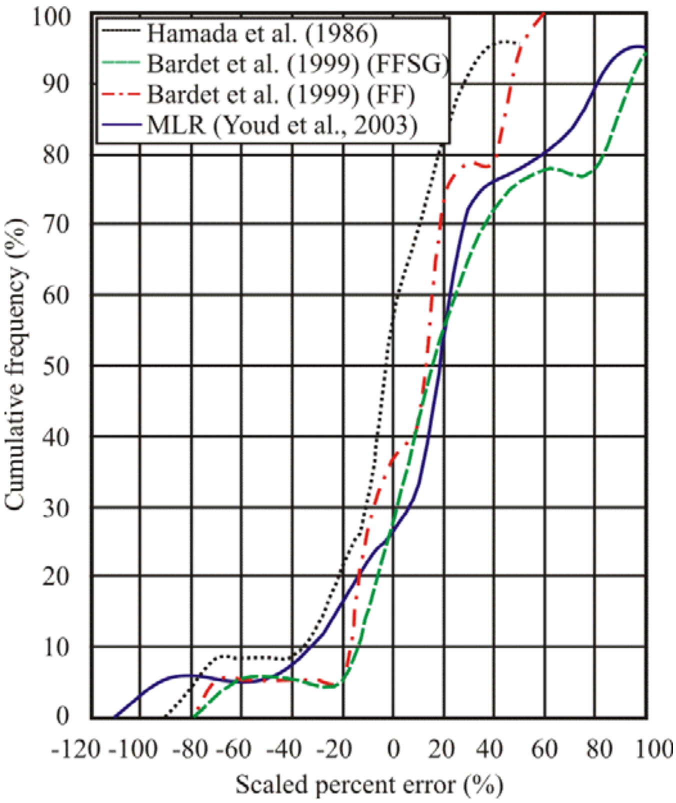

Figure 8. Scaled percent error of the lateral ground displacements predicted from different empirical models (arranged from Kanibir 2003)

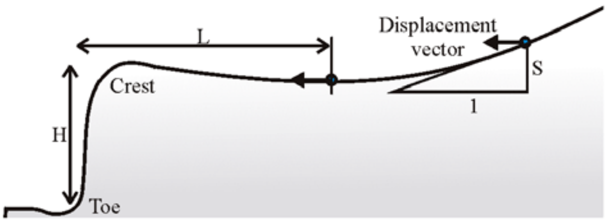

Figure 9. Definition of free-face ratio (W=H/L) and ground slope S (Bartlett & Youd 1992)

Bartlett & Youd (1995) suggest that lateral spreading is generally restricted to soil deposits having $(N_1)_{60}$ values less or equal to 15 for M≤8 earthquakes. By considering this, soil property parameters of the layers with $(N_1)_{60} \leq 15$ were employed in multiple regression analyses as considered by some existing empirical models mentioned above. These parameters are defined and their ranges in the Sapanca database are given in parentheses in Table 1. In the first series of analyses only the database from Sapanca were used, while the second series of analyses were based on the combined database.

Table 1. Parameters employed in regression analyses

Parameter	Definition
Earthquake source and path parameters	
M_w*	Moment magnitude (7.4)
R	Shortest horizontal distance from a site to sesimic energy source (km) (1.01-2.01)
R'	Added distance term from the consideration of distance saturation effects in the near source region ($R'=R+10^{(0.89Mw-5.64)}$ in km; Youd *et al.* 2002) (9.84-10.84)
Topographic parameters:	
W†	Free-face ratio (W=H/L; see Figure 9) (%) (1.00-20.00)
S‡	Ground slope (%) (1.02-3.45)
Material property parameters:	
$(N_1)_{60}15$	Corrected $(N_1)_{60}$ values less than 15 (5.40-14.70)
$D50_{15}$	Average mean grain size for granular materials within T_{15} (mm) (0.05 – 2.33)
F_{15}	Average finer content for granular materials within T_{15} (%) (0.67-9.87)
T_{15}	Cumulative thickness of saturated granular layers with corrected blow counts $(N_1)_{60}$ < 15 (m) (0.67-9.87)

* Not used for the models based on only Sapanca database
† Used for free-face condition
‡ Used for sloping-ground condition

Based on the regression analyses for the Sapanca database, among the equations developed the following models yielded the highest correlation coefficients, r, and are significant at 95% confidence level for FF, SG and FFSG conditions, respectively.

$$D_H = 17.82 + 0.04\,W + 1.88 \log (D50_{15} + 0.1) - 8.02 \log (100-F_{15}) - 0.71 \log (T_{15}^{0.5}) \quad \text{(FF case, r = 0.79)}$$

$$D_H = 19.46 + 0.52\,S + 2.11 \log (D50_{15} + 0.1) - 8.39 \log (100-F_{15}) - 0.54 \log (T_{15}^{0.5}) \quad \text{(SG case, r = 0.80)}$$

$$D_H = 19.34 + 0.5\,S + 0.04\,W + 1.92 \log (D50_{15} + 0.1) - 8.55 \log (100-F_{15}) - 0.46 \log (T_{15}^{0.5}) \quad \text{(FFSG case, r = 0.80)}$$

To show the predictive performance of the above equations, measured displacements at Sapanca using aerial phtogrammetry technique are plotted against those predicted by two models (Figures 10). The solid diagonal line in these plots represents a perfect prediction line. The lower line represents a 100% over-prediction bound and the upper line represents a 50% under-prediction bound. Approximately 60% of the predictions fall onto or are very close to the 1:1 line and 90% of them fall between these two prediction lines. This result suggests that above given models are generally accurate within plus or minus a factor of two. In addition to this comparison, a graph between the scaled percent error (SPE) given below and cumulative frequency is drawn (Figure 11) for the Sapanca database to show the performance of the models.

$$SPE = (D_H - D_M) / (D_{Mmax} - D_{Mmin})$$

where D_H and D_M are the predicted and measured ground deformations, while D_{Mmax} and DM_{min} are the maximum and minimum measured ground deformations, respectively. As seen from Figure 11, about 85-90% of the ground deformations predicted from FF and SG models fall into ±20% of the scaled percent error indicating a better estimate when compared to those from existing models (Figure 8) for the studied case. In addition, FFSG condition suggests slightly better estimates than those from FF and SG conditions (Figure 11). It is also noted that these three prediction models with highest correlation coefficients do not include $(N_1)_{60}$. This situation is probably due to the fact that the other soil property parameters such as $D50_{15}$, F_{15} and T_{15} well represent $(N_1)_{60}$.

Similarly, the second database composed of combination of the world-wide data and Sapanca data were also analyzed. Among the developed models, the following models yielded highest correlation coefficients.

For free face condition (r = 0.87):

$$\log D_H = -20.71 + 1.15\log W - 0.84(\log D50_{15} + 0.1) - 0.02F_{15} + 0.19T_{15}^{0.5} - 1.39 \log R' - 0.009R + 25.23M_w$$

For sloping-ground condition (r = 0.85):

$$\log D_H = -7.52 + 0.11S - 0.89\log (D50_{15}) - 0.22F_{15} + 0.6\log (T_{15}) - 0.23 \log R + 0.001R' + 8.44\log M_w$$

For free face–sloping ground condition (r = 0.86):

$$\log D_H = -18.84 + 0.06S + 0.09W - 0.9\log (D50_{15} + 0.1) - 0.02F_{15} + 0.46\log (T_{15}) - 1.31 \log R' - 0.009R + 23.37M_w$$

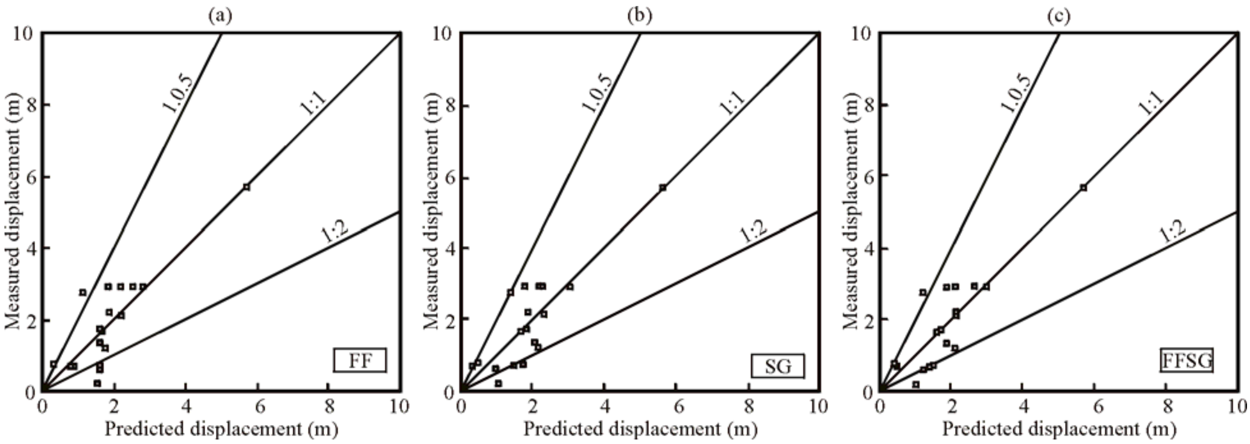

Figure 10. Measured versus predicted displacement for FF, SG and FFSG conditions calibrated from the Sapanca database

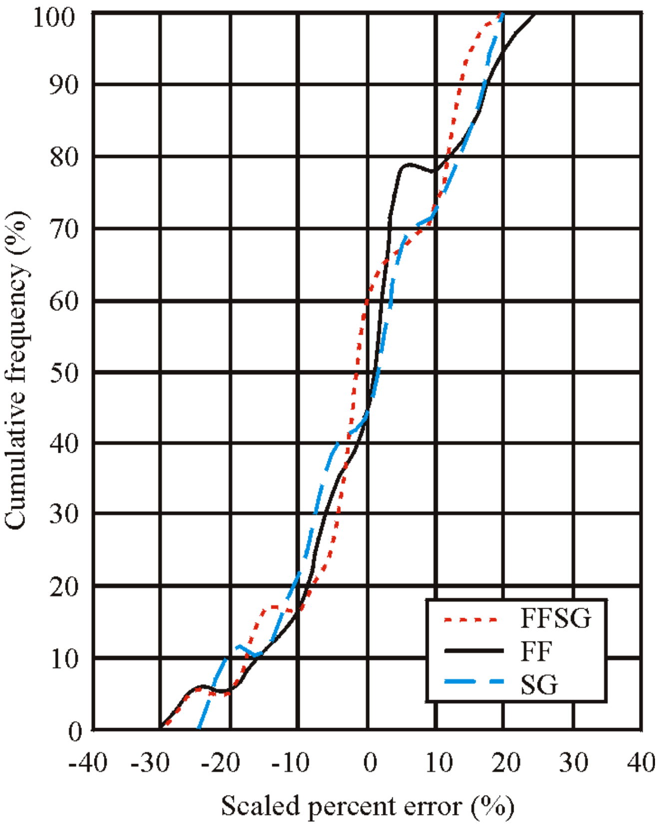

Figure 11. Scaled percent error of the lateral displacements predicted from the models suggested in this study for the Sapanca database

Figure 12 compares the measured lateral displacements and those calculated from the above three models. As seen from this figure, with relatively few exceptions, almost all points fall between the bound lines. SPE – cumulative frequency graphs for FF, SG and FFSG conditions, reveal that about 85-90% of the ground deformations predicted from these models fall into ±20% of the scaled percent error indicating a good estimate as also obtained from the models based on only Sapanca dataset (Figure 13).

CONCLUSIONS

In this study, liquefaction and liquefaction-induced ground deformations on the shore of Lake Sapanca during the Kocaeli earthquake of Turkey were evaluated and empirical models for predicting horizontal displacement resulting from lateral spread were formulated using seismological, topographical and soil property data obtained from both Sapanca and elsewhere. Liquefaction at Sapanca during the 1999 Kocaeli earthquake appears to have occurred primarily within Quaternary alluvial fan deposits at depths between 1 and 14 m. Liquefaction and associated ground deformations are generally observed along the shore and the creeks. The assessments suggested that liquefaction-induced ground disruption could be observed when the thickness of the liquefiable and non-liquefiable layers varies between 0.5 and 1.5 m, and 3.5 and 5.5 m, respectively, when liquefaction occurs. It is also noted that the estimated thickness of the liquefiable layers compared to that of non-liquefiable layers was generally greater at sites with both sand boils and lateral spread displacement greater than 1 m.

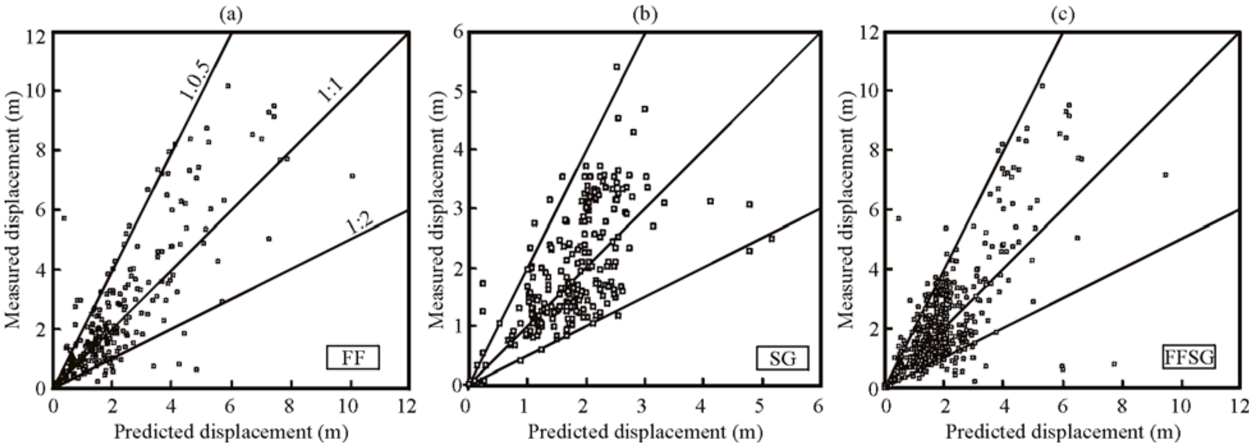

Figure 12. Measured versus predicted displacement for FF, SG and FFSG conditions calibrated from the combined world-wide database.

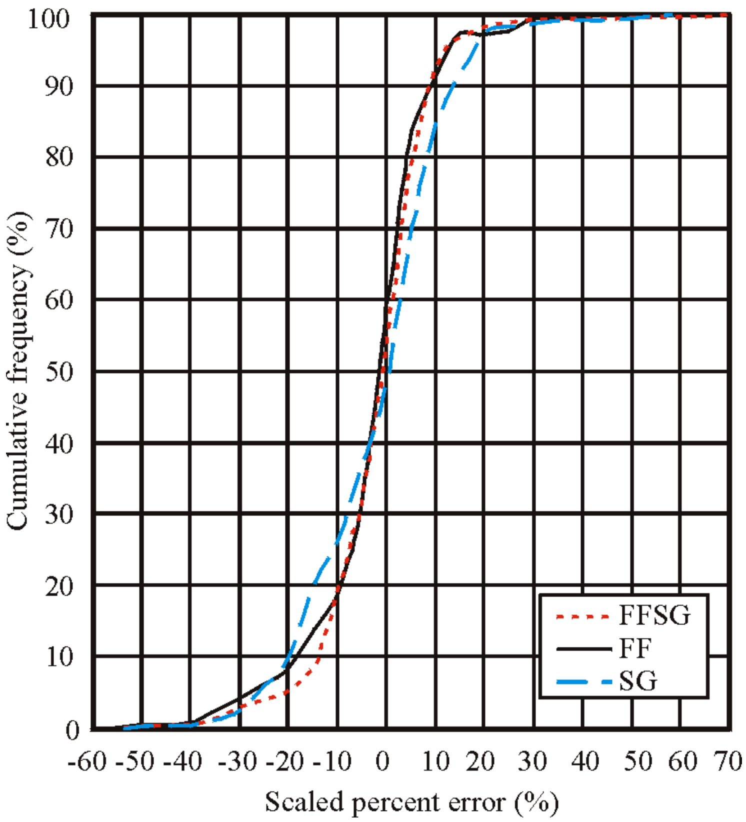

Figure 13. Scaled percent error of the lateral displacements predicted from the models suggested in this study for the world-wide database.

The developed empirical models, which include seismic, topographical and material property data similar to those used by some existing models, generally well predict the measured lateral displacements. About 85-90% of the ground deformations predicted from these models fall into ±20% of the scaled percent error indicating a better estimate for the Sapanca case when compared to those from existing empirical models. It is concluded that in addition to existing models, these equations will provide engineers with a further valuable tool for estimating lateral displacement at sites underlain by potentially liquefiable soils. However, it should be remembered that based on the databases employed in this study, the empirical models developed are valid for $6 \leq M \leq 8$ earthquakes and sandy soils. Therefore, additional research based on new data is needed for further verification of the models and for developing a new generation models. On the other hand, when it is remembered that Sapanca underwent liquefaction and associated ground deformations during the 1967 and 1999 earthquakes, prime consideration should be paid to site selection and remedial measures against liquefaction, particularly along the shoreline.

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