30 Mar 2001, 10:35 am - 11:05 am

General Report — Session 5: Stability and Displacement Performance of Slopes, Landfills, and Earth Dams Under Earthquakes

Donald G. Anderson
CH2M HILL, Bellevue, WA

Allen M. Yourman
Dias Yourman & Associates, Tustin, CA

Hormoz Modaressi
BRGM, France

Azm S. Al-Homoud
American University of Sharjah, United Arab Emirates

Robert C. Lo
Klohn-Crippen Consultants, Ltd., Canada

Recommended Citation

Anderson, Donald G.; Yourman, Allen M.; Modaressi, Hormoz; Al-Homoud, Azm S.; and Lo, Robert C., "General Report — Session 5: Stability and Displacement Performance of Slopes, Landfills, and Earth Dams Under Earthquakes" (2001). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 5.
https://scholarsmine.mst.edu/icrageesd/04icrageesd/session12/5

GENERAL REPORT - SESSION 5

STABILITY AND DISPLACEMENT PERFORMANCE OF SLOPES, LANDFILLS, AND EARTH DAMS UNDER EARTHQUAKES

General Reporter

Donald G. Anderson
CH2M HILL
Bellevue, Washington 98004

Co-Reporters

Allen M. Yourman
Dias Yourman & Associates
Tustin, California 92780

Azm S. Al-Homoud
American University of Sharjah
Sharjah, United Arab Emirates

Hormoz Modaressi
BRGM
Orleans, France

Robert C. Lo
Klohn-Crippen Consultants, Ltd.
Richmond, British Columbia

INTRODUCTION

This General Report provides an overview of 27 papers covering the theme *Stability and Displacement Performance of Slopes, Landfills, and Earth Dams under Earthquakes.* These 27 papers are presented by authors from around the world. Individual authors describe research and design studies that cover a range of methods – from centrifuge testing to case history reviews – and a range of analyses – from simple to highly rigorous, 3-dimensional, effective stress modeling.

For the purposes of this General Report, these 27 papers are separated into two broad categories: (1) stability and displacement of slopes, and (2) stability and displacement of earth dams. A third category involving Other Stability Topics has been added to the General Report to include two papers that involve stability issues but don't fall within the normal definition of slopes, landfills, and earth dams. The broad categories are subsequently broken into a number of subcategories of similar issues, such as methods of analysis, physical model testing, and case histories. Somewhat surprisingly, no papers were received within the general category of stability and displacement of landfill slopes under earthquakes.

The organization of this General Report is in accordance with the general categories identified above. A summary is given for each of the papers. The intent of these summaries is to provide the reader a general overview of the contents of the papers – with the overall goal that the reader will identify papers of interest and then spend the time to read the papers in detail. Following these summaries, a number of general observations, questions, and comments pertaining to the general topic are presented. These general observations, questions, and comments reflect the opinions and interpretation of the general reporter for this session. If these comments are not a fair or accurate interpretation of work by the authors of papers in this session or to the state-of-knowledge in the area overall, the general reporter apologizes.

STABILITY AND DISPLACEMENT OF SLOPES

Fourteen papers are presented in the area of stability and displacement performance of slopes. These papers involve three general areas of work or study: (1) methods of analysis, (2) physical model testing, and (3) case history evaluations. All 14 papers have a common general goal: they are attempting to develop methods or present information that give better predictions or better understanding of permanent slope movement during seismic loading.

Methods of Analysis

A number of methods are currently being used within the consulting profession and academia to predict the movement of slopes during seismic loading. The most common of these methods is the Newmark sliding block method. However, more rigorous computer modeling is also being used on a more regular basis to predict ground movement. Six papers describe evaluations or development with both simplified and more rigorous models.

The first paper in this group, Paper No. 5.01 by Al-Homoud and Tahtamoni, addresses the uncertainty in seismic stability and earthquake-induced displacements of earth slopes and embankments under short-term loading conditions. The authors develop different models for evaluating the probabilistic, 3-dimensional stability of earth slopes and embankments using both safety factor and displacement criteria. Results of a sensitivity study are presented to show the effects of variations in water table location, cohesion and angle of friction, hypocentral distance, earthquake magnitude, and other factors on probabilities of satisfying a prescribed limit. The authors find that hypocentral distance and earthquake magnitude have the most influence on probabilities of failure.

Paper No 5.16 by Beikae questions whether the Newmark method is conservative for inclined slopes. He goes on to explain the reason that this method may not be conservative and presents an alternative methods of analysis, called DSLOPE. Beikae then compares the two methods for three representative cases. For level ground the results are essentially identical but for sloping ground the Newmark method both underpredicts and overpredicts displacements by a factor of as much as 2, depending on the location within the slope.

In Paper No. 5.34 Simonelli and Stefano use the simple sliding block Newmark model to investigate the effects of vertical seismic accelerations on slope displacement. The importance of vertical accelerations is a common question asked in seismic design. Vertical accelerations are usually ignored based on the assumption that the net effect of the upward and downward components will be negligible. The authors confirm this view through a series of analyses for three major Italian earthquakes. Peak horizontal ground accelerations in this study range from 0.15 to nearly 0.4g; vertical accelerations range from 2/3rds to being equal to the horizontal acceleration. For displacements greater than 10 cm, the authors show that the vertical acceleration has a 10 percent or less effect on displacement predictions.

In Paper No. 5.32 a somewhat similar problem is studied by Biscontin, Pestana, Nadim, and Andersen. This paper reports the results of a study of the response of normally consolidated soils on gently inclined, submerged slopes. A simplified, effective stress-based model is used to investigate downslope movement. The soil model is derived from the results of monotonic and cyclic simple shear tests and includes the effects of the initial consolidation state. Hence, the authors' approach clearly is a more rigorous representation of conditions on the slope than a simple yield acceleration within a Newmark model, even when degradation of the yield acceleration with repetitions of load is incorporated. Results of the authors' studies indicate that on sloping ground both the slope and the direction of first earthquake loading affect the predicted deformation. Only minor difference in porewater pressure build-up is noted for the inclined and level ground cases, but differences in spectral acceleration occur at some periods. In the opinion of this general reporter, these results present important information regarding parameters that are relevant to ground displacement prediction. In the absence of these considerations, it appears that the level of uncertainty in the ground displacement prediction, say with a simple Newmark sliding block analogy, is higher and must be considered in presentation of results.

Yourman, Thurai, Nadeswaran, and Diaz (Paper No. 5.15) summarize deformations of slopes for facilities located at the Port of Long Beach and the Port of Los Angeles. In 1991 two of the authors, Yourman and Diaz, compared deformations estimated by the simplified Newmark method for these facilities. Over the past 10 years a number of finite element analyses have been conducted by various consultants for the same facilities. This paper summarizes results of these finite element analyses relative to the previous simplified analyses. A number of finite element modeling methods were involved in the comparison, including programs such as FLAC, DSAGE, DYNAFLOW, and LINOS. These finite element programs use nonlinear soil models, and the modeling of some of the facilities included the pinning effects of piles. The results of the more recent finite element modeling show significant benefits when the pinning effects of the piles are incorporated in the analyses. The authors cite this as one of the benefits of using the more rigorous, 2-dimensional finite element modeling relative to the simplified Newmark method. As a general note, it is also possible to incorporate the effects of ground improvement and pinning within a Newmark analyses by "smearing" the added reaction from the piles or ground improvement over the sliding surface. While this approach has various limitations, it can be used to obtain a first-estimate of the benefits of the structure or ground improvement on limiting deformations. For the case involving pinning of piles, close cooperation between the structural designer and the geotechnical engineer is required to appropriately represent the pinning effects in the simplified model.

The final paper within this topic area, Paper No. 5.21 by Foerster and Modaressi, describes a new approach for large displacement assessment in soils during dynamic loading. These authors report progress towards the development of a "mesh free h-p clouds (HPC) technique" for large-deformation problems. A multiphase, deformable porous medium is represented with this approach. Since this method does not involve the normal mesh constraints, the authors believe that it has significant applications in the area of liquefaction, when lateral flow is being predicted, or in landslide studies.

Physical Model Testing

Four papers in this session involve physical modeling of soils using either centrifuge or shake table testing methods. Results of these tests are used to calibrate existing or new numerical models for predicting the displacement of slopes during seismic loading. This calibration process is critical to the understanding of the validity of predictive methods. The geometry and physical characteristics of the soil in these physical models are usually well-defined, and therefore the results of the physical model test can be used to confirm that the numerical model represents the loading process both spatially and temporally. In the absence of these calibration studies, numerical models can provide very accurate predictions that have little relevance to actual mechanisms occurring in the field. Physical modeling is time consuming and requires significant attention to details, and therefore, the authors of the four groups of papers in this category are to be commended for their efforts.

Only one of the four papers (Paper No. 5.06 by Wakai, Ugai, Sato, and Tazo) reports on the use of the centrifuge. These authors conducted their tests on a clay slope. A shake table in the centrifuge was used to shake the slope. Results from these physical model tests are compared to predictions from a 2-dimensional, finite element computer model. The soil model in the finite element code is a modification to the Ugai-Wakai constitutive model. This model includes the effects of shearing strain amplitude on shear modulus and material damping, as well as stress dilatancy. Good agreement is found by the authors when the results of finite element modeling, including permanent deformations and settlement, are compared to the results of the centrifuge tests. The authors comment that one of the benefits of their proposed effective stress soil model is the limited number parameters needed.

In Paper No. 5.14 Wartman, Bray, and Seed also investigate the behavior of cohesive slopes, but with a large shake table. These authors specifically mention that they considered the laws of similitude when developing their model, since the shake table tests are conducted at 1g (g = gravitational acceleration). Displacements were recorded in the shake table tests for both initial and residual conditions. Results of the shake table tests are compared to those predicted by a Newmark-type sliding block model within the computer program YSLIP_PM. One of the significant features of this numerical model is that it allows the progressive degradation of the yield acceleration – a conditions that is likely to occur in clay slopes that undergo high levels of seismic loading. The authors observe that the Newmark model within YSLIP_PM seems to provide a moderately accurate estimate (i.e., within 40 to 85 percent) of seismically induced permanent displacements and that the accuracy is better (1) when the degrading model is used and (2) for the residual shear strength case. The latter observation is attributed to the more stable conditions for the residual loading phase of the test. These results again seem to point out the uncertainty associated with use of the Newmark modeling method and, in this case, the importance of including a degrading yield acceleration. Often these details are neglected during deformation predictions, and these clearly could affect the accuracy of the prediction.

Two papers report on the use of shake table modeling as part of studies of slope stabilization methods. The first paper by Mizutani and Towhata (Paper No. 5.24) describes shake table tests on saturated sandy materials. Their purpose is to investigate the use of sheetpiles to stabilize dikes in Japan during large earthquakes. If these dikes were to fail, large areas could be flooded. Economics precluded the use of normal ground improvement methods: sheetpiles were however considered to be a viable alternative. The model tests are used to evaluate the displacement of a model dike – with and without sheetpiles. The effects of the sheetpile location, as well as the use of vertical drain pipes, are also investigated. Results of these model tests confirm that sheetpiles will limit vertical and lateral displacements. The sheetpiles are found to be more effective when placed at the top of the slope and when combined with a drainage system behind the wall. These shake table tests were conducted at 1g, and therefore it is not clear whether some of the absolute results might differ for full-scale conditions. Nevertheless, the results clearly confirm the benefits of the sheetpiles and drainage systems, as would be expected. The authors conclude with the comment that this concept of stabilization might be applied for other liquefaction problems. This conclusion is consistent with work conducted in a centrifuge as part of earthquake studies at the Multidisciplinary Center for Earthquake Engineering (MCEER). The MCEER work involved the use of sheetpile walls to stabilize roadway embankments (Adalier, et al., 1998).

The final paper in this group (Razavi and Kimura, Paper No. 5.09) involves the use of shake table tests to investigate the effects of rock bolts and rope nets on the stabilization of slopes during earthquake loading. This study was initiated by the authors after the observation of large landslides and slope failures as a result of the 1995 Hyogoken-Nambu earthquake. A decomposed granite ($\phi = 31^{\circ}$; c = 8 kPa) was used in the model. Up to 0.25g was imposed to the 1 vertical to 1 horizontal slopes with different combinations of simulated rock anchors and rope nets. Both sharp- and rounded-corner slopes are evaluated in the physical model tests and in subsequent numerical simulations. The computer program DYNAFLOW is used to conduct the numerical simulations. A Drucker-Prager criterion is used to represent the soil in DYNAFLOW. Beam and truss elements are used to represent the rock bolts and rope nets, respectively. The authors report that the rock anchors and netting are able to reduce slope displacements and that the calculated and measured deformation at the top of the slope are in agreement – though the authors also note that parameter study and material calibration "seems to be necessary."

Case Histories

Four papers report evaluations of observed ground displacements during seismic loading. Two of the cases involve displacements related to porewater pressure build-up, one involves observed movement of a rock slope, and the fourth deals with a large area evaluation of landslides in India following the 1999 Chamoli earthquake.

In the first of two papers involving porewater pressure build-up (Paper No. 5.38), Kokusho and Fujita relate the displacements during lateral flow failures to the development of water films with no shear resistance at the base of fine-grained material. This water film is postulated as creating a sliding surface for post-liquefaction flow failures. These authors support their concept by presenting the results of a careful re-interpretation of soil conditions, ground elevations, and ground displacements for an area that moved during the 1964 Niigata earthquake. The authors find that up to 4 m of displacement occurred at slopes of 0.5 percent, and that the only physical explanation for this amount of displacement could be sliding on a water film. This phenomenon could potentially present a significant design concern for some sites – first in trying to identify whether the phenomenon could occur and then in quantifying the potential amount of displacement.

The second study involving porewater pressure build-up is presented by Loukidis, Lee, Yi, and Bourdeau (Paper No. 5.31). These authors investigate the deformation of the Nikawa landslide, which occurred during the 1995 Hyogoken-Nambu earthquake. This sliding mass moved more than 150 m at a high velocity. A sand layer located below the water table is believed to have liquefied during the earthquake. Pseudo-static, sliding block (Newmark), and 2-dimensional, nonlinear effective stress (FLAC) analyses were conducted to evaluate the landslide mechanism. The FLAC analyses confirm that porewater pressures could develop, and the mobilized apparent friction angle ($\phi = 7^{\circ}$) interpreted from the FLAC analyses is consistent with laboratory measurements. When similar low apparent friction angles are used in the pseudo-static and Newmark analyses, the authors report that results are consistent with the observation of large displacements. Again, these results seem to indicate that available methods of analysis provide reasonable representations of earthquake loading, if the site and material properties are appropriately characterized.

In Paper No. 5.04 Cummings presents results of a detailed post-earthquake evaluation of spalling of a rock slope. This case study is based on observations made after the 1994 Northridge earthquake in southern California. The author describes a simple analytical model for the earthquake-induced spalling of rock produced by incident compressional waves oriented normal or oblique to a free surface. Cummings indicates that the simple method can be used to estimate location and thickness of potential spalled slabs by using (1) site-specific rock properties from laboratory and field geophysical measurements and (2) expected seismic properties from a design earthquake, attenuated to the site. One of Cummings' key conclusions is that spalled slabs can occur on fairly gentle slopes, and not just on vertical or near-vertical free surfaces such as cliffs and bluffs.

The final paper in this group of papers is authored by Nainwal and Naithani (Paper No. 5.37). These authors report on the occurrence of landslides in the Garhwal-Kumaun region of the Himalayas during the 1999 M6.8 Chamoli event. The maximum ground acceleration for this event was estimated to be 0.2g. Landslides, fissures, and terrain changes are reported to have occurred over a 1800 square kilometer area. Over 100 new landslides occurred and 17 old landslides were reactivated. Fissures are reported to have ranged from 1 to 50 cm in width and from a few meters to 500 m in length. The authors conclude with an ironic warning, given the recent earthquake in India: "*It is surprising that at present little concern is shown towards protection of housing, community buildings, temples and monuments which have not been provided any earthquake resistance features at all and the collapse of which in such a calamitous earthquake occurrence, could lead to loss of a hundred thousands lives. It is high time that an appropriate damage scenario is worked out and people warned of the consequences of such a prediction coming true.*"

STABILITY AND DISPLACEMENT OF DAMS

Eleven papers are presented on the general topic of stability and displacement performance of dams. These papers are divided into three general areas of work or study: (1) design and remediation, (2) case studies of dam performance, and (3) earthquake modeling and sensitivity studies. As with the 14 papers dealing with the response of slopes, these papers all seek to present information that results in improved understanding and performance of dams during future seismic events.

Design and Remediation

Two papers focus their presentations on the current approach to design and remediation of earth dams. Both papers provide valuable information to consider during the design of new dams and the seismic stability assessment of existing dams.

In Paper No. 5.08 Lo, Klohn, and Finn provide a summary of seismic design procedures for tailings dams. These three individuals are internationally respected for their significant experience in practical design issues, as well as the application of rigorous modeling methods; and therefore, their paper presents valuable guidance to the reader. Their paper includes a review of the evolution of tailings dam construction methods, a summary of tailings dam failures, and a summary of key factors affecting the seismic performance of tailings dams. These discussions are followed by a summary of recent trends and challenges in tailings dam design and construction, including the public perception and environmental demands associated with siting tailings dams. The authors also summarize some of the technological tools that are and should be used during the seismic design of tailings dams. Of particular importance is their reference to (1) the use of residual strength in the liquefaction stability evaluations, (2) the applicability of non-linear, effective stress computer programs, (3) the role of risk assessment, and (4) the alternatives for enhancing the safety of dams through various ground remediation methods. While the paper is written with a focus on tailings dams, many of the discussions are appropriate for the design of any slope, where liquefaction is potentially of concern.

A second paper by Uddin and Baltz (Paper No. 5.05) also focuses on current design and remediation measures. These authors describe methods that they used to investigate and then remediate a dam on the Muskegon River in Michigan. Their seismic assessment involved the use of FEADAM and SHAKE. The potential for liquefaction in one of the embankments led to an evaluation of liquefaction remediation methods. These included the use of drains, vibroflotation, jet grouting, compaction grouting, toe berms, and flattened slopes. Relative costs for these methods are presented, and an approach for bidding alternate methods of remediation is described. While the costs and approach will likely vary for other dams, the methodology used by the authors to investigate the conditions and to develop a remediation plan represents the state-of-the-practice in the United States for handling such requirements.

Case Histories

Three papers cover case histories of dam performance during large seismic events. Two of the studies involve the 1995 Hyogoken-Nambu earthquake in Japan; the other deals with the 1999 Chi-Chi earthquake in Taiwan. In all three studies an attempt is made to simulate the observed response of the dams using numerical methods.

Iwashita describes work that he did for the Kitayama Dam in Paper No. 5.13. The upstream slope of this dam slid along a length of nearly 100 m. While the damage wasn't significant, it was the first dam built by rolling compaction that had been damaged in this way. The author summarizes in situ and laboratory tests completed after the earthquake as part of the study, as well as the dynamic analyses that were conducted to investigate response. An effective stress analysis method with an elasto-plastic, soil densification model is used in the computer program MuDRAIN to perform the analyses. The soil model includes a porewater pressure build-up mechanism. Results of Iwashita's analyses seem to be consistent with the observed damage – bulging of the sliding block around the upstream toe and drop of the sliding block at the water level. Effective stresses are also predicted to drop significantly during shaking suggesting that liquefaction of some layers occurred, resulting in the observed displacements. These results suggest that reasonable simulations of seismic response can be achieved, given appropriate models of the geometry, soil conditions, and ground shaking level.

The next case history (Paper No. 5.27) involves an evaluation of the failures of two irrigation dams. This paper is presented by six co-authors: Uchida, Higasio, Torii, Yamamoto, Tsujino, and Ando. These authors describe their analyses of the 9-m high Idenoshiri-Ike dam, which collapsed completely, and the 12-m high Sugatadani-Ike dam, which was damaged by a large slide along the upstream slope. Two numerical methods are used during these evaluations. For the Idensoshiri-Ike dam the computer program TARA is used to investigate the effects of liquefaction. TARA is a 2-dimensional, nonlinear effective stress code. The computer programs FLUSH and TARA are used for the Sugatadani-Ike study. The authors conclude from this study that the observed deformations are associated with liquefaction and could only be represented when porewater pressure increases are included in the computer simulation

The final paper in this group of case histories (Paper No. 5.20) is written by Chern and Tsai. These authors present two case histories from the 1999 Chi-Chi earthquake – one for the Shuisheh Dam and the other for the Liyutan Dam. The intent of the case history study was to compare observed deformations with deformations predicted by the "Seed-Lee-Idriss semi-analytical approach." Although the Seed-Lee-Idriss method is relatively old, it is commonly used in Taiwan for the design of earth dams. The Shuyusge dam is roughly 30 m in height and underwent some cracking and deformation (e.g., bulging and settlement) during the Chi-Chi earthquake. The Liyutan dam is approximately 96 m high and was newly completed. Cracks were observed along the abutments of this dam. Due to the very low width to height ratio, 3-dimensional analyses were also completed for the Liyutan Dam. The authors report that the results of their analyses using the Seed-Lee-Idriss approach are consistent with the observations, giving them general confidence in the Seed-Lee-Idriss method for well-compacted earth dams.

Numerical Methods and Sensitivity Studies

The final set of six dam-related papers deals with numerical modeling or sensitivity studies for dams. The authors of these papers use a variety of numerical methods to perform their studies. These methods ranged from an extension of the previously reported sliding block (Newmark) method to 3-dimensional, effective stress models.

Sarma and Cossenas extend the work performed previously by Ambraseys and Sarma in Paper No. 5.19. These authors use a database of free-field motions to develop estimates of displacement as a function of the period for a dam with 1 vertical to 3 horizontal slopes. Displacements are tabulated for different ratios of sliding surface location to dam height and for different probabilities of exceedance. Spectra of average seismic coefficients as a function of height ratio are also presented. The authors note that these results can be used as a check on the safety of earth dams under seismic loading but warn that the displacement could be one order of magnitude different than displacements from computed ground motions. This second comment by the authors is significant, in that it reiterates the limitations associated with simplified predictive methods. Significant variations in deformation clearly must be anticipated when these simplified procedures are used. This is not to imply that more rigorous computer modeling is necessarily any more reliable in deformation predictions. While these more rigorous methods may show results to several decimal points of accuracy, assumptions on boundary conditions, soil characterization, and input motion selection can introduce as much if not more uncertainty than the simple methods.

The next paper (No. 5.07) by Zhou, Chi, and Qi describes analyses performed using 3-dimensional, effective stress modeling methods. These authors study the response of the Taiyuan Fly Ash Dam. This dam has a height of nearly 96 m and a length of 258 m. The nonlinear response of the soil is represented by the Hardin-Drnevich hyperbolic model; the simplified Seed procedure is used to introduce porewater pressure increase. Results of these analyses show the distribution of shearing stresses and porewater pressure increases. The limiting acceptable height of the dam and remediation methods are defined from this information.

Zhao and Wang (Paper No. 5.12) also study the response of a dam using 3-dimensional, nonlinear effective stress methods. Their method allows the dissipation of porewater pressures during shaking. They also take into account the residual shearing strain and residual volumetric strain during the estimation of deformations. Methods for conducting the 3-dimensional response analyses are presented, and the evaluation of the earthquake-induced permanent deformations is described. The use of this method is demonstrated for Zipingpu dam – a 156-m high, concrete-faced, rockfill dam. These results include contours of acceleration, dynamic shearing stress, and deformations.

The paper by Wu, Luan, and Xin (Paper No. 5.22) also deals with the response of concrete-faced rockfill (CFR) dams. These authors use an equivalent linear procedure in 3-dimensional seismic response analyses to investigate the sensitivity of response to different material property assumptions. Different combinations of small-strain shear modulus, as well as strain-dependent modulus and damping, are evaluated. This study was carried out on the 182-m high Hongjiadu CFR dam in the southwest area of China. The authors conclude that the property assumptions will affect some of the seismic response predictions. The authors also conclude that "reasonable selections of dynamic parameters of rockfills should be made prudently in order to confidently evaluate the earthquake-resistant behavior of concrete-face rockfill dams from 3-dimensional, equivalent-linear seismic analyses." It would seem that this recommendation applies to all types of dynamic analyses. In light of the uncertainties in material property characterization, constitutive modeling, and the selection of earthquake ground motions, all prudent designers should be trying to quantify these uncertainties on predicted response.

The final two papers in this group (Paper Nos. 5.39 and 5.41) are presented by Khusanov and Umarkhonov and by Umarkhonov from Uzbekistan. In the first paper Khusanov and Umarkhonov present methods for evaluating the dynamic behavior of earth dams with and without moisture content effects on the clay core. The dam material is evaluated as elastic and elastic-plastic materials; finite difference methods are used to define response. The method of analysis is demonstrated for the 168-m high Charvak dam. Results are presented to show the development of plastic deformations with time. In the second paper Umarkhonov uses similar methods to study the development of plastic deformations during seismic loading.

OTHER STABILITY TOPICS

Two other papers are covered in this session. These papers do not deal strictly with the stability and displacement of slopes and dams. Rather, one deals with the dynamic stability of tunnels in jointed rocks, and the other describes dynamic analyses for evaluating the stability of intake structures for a dam.

In Paper No. 5.25 Naderi, Hataf, and Ghahramani describe use of discontinuous deformation analysis (DDA) methods to investigate the dynamic stability of tunnels in jointed rocks during seismic loading. The DDA is extended to include damping and energy loss occurring during a seismic event. Detailed descriptions of the DDA formulation are presented, and two illustrative examples are described. The authors conclude by stating that the results of this development are very promising and similar to results of block theory. They also note that block displacements and deformations of the roof of the tunnel generally match with field observations.

The final paper (No. 5.33) by Gatmiri, Vossoughi, and Jenab-Vossoughi presents a 3-dimensional finite element model for analyzing problems related to the construction of complex geotechnical structures, such as earth dams, tunnels, and retaining structures. The model uses an elasto-plastic constitutive model of the soil. The authors apply this method of analysis to a circular shaft and two tunnels at the Lar Dam, an earth dam located about 120 km from Tehran. The paper describes the method of analysis, including the model, material properties, and the results of static and dynamic analyses. The authors report that results of the analyses provide a more complete picture of response than would have been obtained by 2-dimensional plane strain or plane stress models. The authors also note that the main difficulties with the analyses were the capacity of the computers and the processing time. A dynamic modal analysis with 10 mode shapes took about 44 hours to run on a SUN (SPARK Station 20) computer.

GENERAL COMMENTS AND OBSERVATIONS

The 27 papers discussed in this General Report provide a significant overview of methods being used currently by practitioners and academia to investigate or predict the performance of slopes and dams under earthquake loading conditions. These methods range from physical model tests using shake table and centrifuge methods to field investigations of observed ground movement. They also include the development of new constitutive soil and computer models. The following observations and comments are made regarding these papers. These comments and observations include questions regarding the general topic. Although there were no papers on the topic of landfills, this General Report also provides some comments and questions in this area as well.

Stability and Displacement of Slopes

From this set of papers it is evident that two approaches are being used to predict the stability and displacement of slopes during seismic loading. One involves the simplified Newmark sliding block method, or versions thereof; the other involves use of rigorous 2-dimensional, nonlinear effective stress modeling methods. There are clear advantages and disadvantages of each. Practicing engineers need a simple method such as the Newmark sliding block method to quickly obtain an estimate of displacements. But in many situations the simplified methods cannot properly account for boundary conditions, soil behavior such as porewater pressure build-up, structural systems in the slope, and details of the seismic environment. On critical projects, when these details are important, the use of more rigorous methods is required. This suggests that development and validation in both areas, such as described in the papers in this session, need to continue.

A number of questions arise relative to the use of the simplified methods:

- *What level of accuracy should be assigned to results of the Newmark sliding block analyses*? For example, displacements are often presented to the nearest centimeter (0.1 inches). If chart solutions are used, should the results be reported to anything less than 150 mm (6 inches)?

- *What chart methods should be used and in what situations?* For example, methods have been presented by Franklin and Chang (1977), Makdisi and Seed (1977), Wong and Whitman (1982), Hynes and Franklin (1984), Martin and Qiu (1994), and others. Each method was developed with somewhat different assumptions. More often than not, the basis of development is not understood by the user. More guidance in this area would seem to be appropriate.

- *What limitations exist with the direct integration of earthquake records?* It would seem that the critical decision is the selection of earthquake records. However, as pointed out in Paper No. 5.32, the existing stress bias and the direction of first excursion of the earthquake record also can have a significant effect on displacement predictions. Similarly Paper No. 5.14 indicates that the use of degrading yield accelerations provides better comparisons between measured and predicted displacements. These effects need to be factored into the use of any of the predictive methods, whether they are simplified chart solutions or rigorous 2-dimensional finite element (or difference) modeling.

Numerous questions can also be asked of the more rigorous numerical modeling methods. For example,

- *How are uncertainties in boundary conditions and material properties quantified and introduced into the predictive method?* From a practical standpoint simplifications have to be made when setting up these models. The effects of these simplifications are often hard to predict a priori. Clearly, this emphasizes the need for parametric studies and calibration checks against simpler methods or against published case history data.

- *Are the current models used for structures and soils in these computer programs capturing the essence of soil-structure interaction during seismic loading?* Simplified representations of the soil and the structure are often used. It is not always clear whether these methods adequately represent the behavior of the soil and structure during seismic loading, particularly when large deformations are involved.

- *How do we develop confidence in the integration of these rigorous methods into design?* It is now possible to purchase a program such as FLAC for under $10,000 (US), which is well within the budgets of many geotechnical consulting firms. With the ease in setting up the model in this computer program, a consulting engineer can quickly obtain results. But when should the owner or user have confidence in these results? It is clear that the user must have good training on the limitations of the program and must have a good "sense" when the results are meaningful. As noted above, this situation also emphasizes the need for validation checks against results of physical model tests or observed field conditions.

The need for calibration studies is critical for improving the confidence of the profession in any displacement predictions. These types of experiments and case studies should be continued. However, important questions regarding the collection or performance of these tests must be addressed.

- *What level of field exploration is needed to make a back analysis meaningful?* If too much uncertainty exists in boundary conditions, material properties, or the earthquake input motions, then the validation study has limited value.
- *What limitations exist with physical model tests?* For example, shake table tests at 1g on saturated cohesionless soils present difficult scaling issues that must be considered when interpreting results. From this standpoint it would seem that centrifuge tests should be emphasized when studying liquefaction phenomena.
- *What large-scale testing might be carried out to study slope stability and displacement during earthquake loading?* Ideally, marginally stable slopes or areas susceptible to lateral spreading will be instrumented to capture the development of porewater pressures, cyclic and permanent displacements, and the like during seismic events. However, these field instrumentation programs are very costly and often involve extended periods of monitoring. As an alternative, perhaps experiments involving blast loading similar to work conducted on pile response at Treasure Island, California might be conducted.
- *Is there still a need for laboratory testing to develop material models that account for stress biases, dilatancy and contraction, and strain amplitude effects?* Even with laboratory testing programs, the issues of sample disturbance must be addressed. The ability to adequately quantify the effects of sampling on important soil properties would still seem to present questions.

These questions on confidence and uncertainty point to the need for more emphasis on probabilistic approaches to dealing with stability and displacement during earthquake loading studies. The ground motion used as input is often described in a probabilistic framework, but a deterministic approach is used for quantifying the effects of these motions on the performance of the slope. More attention is being given during the design of buildings and bridges to performance-based design, where deformations are quantified in a probabilistic sense. This same approach is needed for estimating the probability of slope performance during earthquake loading. Paper 5.01 presents an example of this approach.

Another general need pointed out in Paper No. 5.37 involves quick screening methods of large areas for seismic-induced landslide stability. For example, topography in combination with general geology and probable levels of earthquake shaking might be used to identify areas potentially susceptible to landslides. These methods might be used to quickly identify areas or routes along highways to stabilize or vacate. It was apparent from the 1999 Chi-Chi earthquake that landslide can lead to closure of highways and significant disruption of commerce.

Stability and Displacement of Dams

The 11 papers dealing with the performance of dams during seismic loading cover topics ranging from design and remediation to new numerical modeling methods. The types of dams range from liquefaction-sensitive tailings dams to rock-filled dams with heights of over 150 m. These topics would seem to involve many of the same questions as noted above for slopes subjected to seismic loading.

In the area of material characterization, a number of questions appear to be important for realistic modeling of the response of a dam to seismic loading. For example,

- *What procedures should be used to characterize the modulus and material damping properties of rockfill dams?* Are the conventional modulus and damping curves developed by Seed-Idriss, Hardin-Drnevich, and Dobry and Vucetic appropriate for these materials. If not, how should these properties be determined.
- *Are new liquefaction models needed to more accurately represent the contractive and dilative behavior of sands during seismic loading, as is essential for analyses of tailings dams involving liquefiable materials?* Major emphasis has been placed on the determination of liquefaction potential using Standard Penetration Tests (SPTs) and Cone Penetrometer Tests (CPTs) over the last decade. While these tests provide the user with critical information about performance at failure conditions, they give little information about the effects of confining stress, initial shearing stress, and the contractive or dilative characteristics of the soil. It would seem that additional focus needs to be placed on these topics.
- *Are there special considerations associated with the large effective stresses associated with 150-m high dams?* Fortunately, it appears that most observed displacements of slopes for dams have been in the upper levels where stresses are lower and therefore this point may not be important.

With the rapid advances in 2- and 3-dimensional nonlinear, effective stress computer models, the use of these methods to predict seismic performance is bound to increase. While these models often appear to provide meaningful results, questions still exist on the confidence that the profession should attach to the use of some of these methods.

- *What methods of calibration should be used to confirm that the computer method is providing meaningful results?* It would seem that new methods should be validated against centrifuge test results as a minimum. Perhaps the profession needs to have standard calibration models to check the use of new computer programs or new users to existing programs.

- *When should rigorous 2- or 3-dimensional methods be used versus simpler methods (e.g., the Seed-Lee-Idriss method discussed in Paper No. 5.20)?* While the more rigorous approaches do more "things", they do not necessarily provide more confidence in what is being done. Often the uncertainties of boundary conditions or material behavior mask the actual performance to the extent that simpler methods may be as reliable.

As with the above discussion of slopes, it appears that the performance of dams during seismic loading also needs to be considered in a probabilistic manner.

Stability and Displacements of Landfills

No papers were received for this session in the area of stability and displacement performance of landfill during seismic loading. This is somewhat surprising, as in the past this has been the topic of various papers including state-of-the-practice presentations. Various work continues in this area, as summarized below.

- The deformation of landfill slopes is critically dependent on the characterization of the strength and deformation properties of landfill waste. Kavazanjian and his colleagues at GeoSyntec, Huntington Beach, California have published a number of papers over the past 5 years discussing these properties (e.g., Kavazanjian, et al., 1995 and 1996; Kavazanjian and Matasovic, 1995; Matasovic and Kavazanjian, 1998). Reference should be made to these papers when approaching landfill stability problems.

- In situ testing using the CPT and the Spectral Analysis of Surface Wave (SASW) methods has been relatively successful in characterizing landfills in a number of cases. These indirect methods avoid some of the problems of handling contaminated waste while still providing information that can be used to determine the strength and stiffness of the landfill material.

- The importance of degrading yield accelerations has also been identified for deformation estimates (Matasovic, et al., 1997).

- A variety of numerical methods have been used to estimate the response of landfill slopes to seismic loading. These have varied from simple Newmark methods to 2-dimensional finite element models. Recent papers by Kramer and Smith (1997), Bray and Rathje (1998), and Rathje and Bray (2000) present important information regarding the effects of stiffness of landfill materials on the accelerations that occur within the landfill deposits. These papers should be consulted when simplified methods are being used to predict deformations.

A number of questions need to be addressed in the area of landfill design:

- *What deformation criteria should be used during the design of landfills?* The acceptance criteria for landfill displacements is often specified as 300 mm or less. Most often this limit is cited for landfill liners, but it has also been required for landfill covers. A significant question regarding this criterion occurs – whether any of the available methods can reliably estimate displacements to this degree of accuracy, particularly on a localized basis. For cover systems it would seem that a larger displacement criterion should be allowed, as normally it is more cost effective to repair a cover than to design to displacements of 300 mm. However, the criterion for bottom liner is another matter, and poses a significant dilemma. Additional consideration in this area appears needed.

- *How much reliance can be placed on the empirical relationships between CPT results and landfill strength?* On some projects the trend has been to rely on CPT soundings to estimate the strength of landfill deposits, prior to conducting a deformational analysis. This poses a question as to whether the normal methods of converting q_c to undrained strength using N_k are correct, particularly when leachate with various characteristics has percolated through the material.

- *Is there still a need for collecting seismic response information for landfills, and who should pay for this effort?* Efforts were made in the late 1980s and early 1990s to instrument landfills with accelerometers to collect response information during seismic events. It would seem that this information is still useful, but finding a group to provide maintenance and ultimately interpret the data has not been resolved.

Like the area of slopes and dams, it is apparent that a lot of work needs to be done in the general area of landfill performance during seismic loading.

Closing Comments

This session focuses on the stability and displacement performance of slopes, landfills, and earth dams under earthquake loading. The authors who submitted papers to this session are to be commended for their efforts and their willingness to share their experiences and ideas with the profession at-large. Through this willingness to share ideas and experience, the profession will learn and be able to provide better estimates of performance and more efficient designs in the future. In the end society will benefit.

There are numerous problems to solve in the area of stability and displacement performance of slopes, landfills, and earth dams. It is unlikely that any single method or approach will meet all needs, and it is unlikely that our needs will be quickly solved. Progress will occur as a series of small steps. Each of the contributors to this session is helping to move our understanding forward. This cooperation is appreciated and needs to continue.

In closing, it is hoped that the participants in this session and the readers of papers within the session will be able to look back 20 years from now and feel good about the accomplishments that have been made by building on the good ideas presented and discussed at this conference.

REFERENCES

Adalier, K., A.W. Elgamal and G.R. Martin [1998]. "Foundation Liquefaction Countermeasures for Earth Embankments," Journal of Geotechnical and Environmental Engineering, ASCE, Vol. 124, No. GT6, June, pp. 500- 517.

Bray, J.D. and E.M. Rathje [1998]. "Earthquake-Induced Displacements of Solid-Waste Landfills," Journal of Geotechnical and Environmental Engineering, ASCE, Vol. 124, No. GT3, March, pp. 242-253.

Franklin, A.G. and F.K. Chang [1977]. "Earthquake Resistance of Earth and Rock-Fill Dams; Permanent Displacements of Earth Embankments by Newmark Sliding Block Analysis," Miscellaneous Paper S-71-17, Report 5, U.S. Army Waterways Experiment Station, CE, Vicksburg, MS.

Hynes, M.E. and A.G. Franklin [1984]. "Rationalizing the Seismic Coefficient Method," Miscellaneous Paper GL-84-13, U.S. Army Waterways Experiment Station, Vicksburg, MS.

Kavazanjian, E. and N. Matasovic [1995]. "Seismic Characterization of Solid Waste Landfills," *Geoenvironment 2000*, ASCE Geotechnical Specialty Publication No. 46, pp. 1066-1080.

Kavazanjian, E., N. Matasovic, R. Bonaparte, and G.R. Schmertmann [1995]. "Evaluation of MSW Properties for Seismic Analysis," *Geoenvironment 2000*, ASCE Geotechnical Specialty Publication No. 46, pp. 1126-1141.

Kavazanjian, E., N. Matasovic, K.H. Stokoe, and J.D. Bray [1996]. "In Situ Shear Wave Velocity of Solid Waste from Surface Wave Measurements," Proceedings, 2nd International Congress on Environmental Geotechnics, Balkema, Osaka, Japan, Vol. 1, pp. 97-102.

Kramer, S.L. and M.W. Smith [1997]. "Modified Newmark Model for Seismic Displacements of Compliant Slopes," Journal of Geotechnical and Environmental Engineering, ASCE, Vol. 123, No. GT7, July, pp. 635-644.

Makdisi, F.I. and H.B. Seed [1977]. "Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations," Journal of Geotechnical Engineering Division, ASCE, Vol. 104, No. GT7, July, pp. 849-867.

Martin, G.R. and P. Qiu [1994]. "Effects of Liquefaction on Vulnerability Assessment," NCEER Highway Project on Seismic Vulnerability of New and Existing Highway Construction, Year One Research Tasks – Technical Research Papers.

Matasovic, N., E. Kavazanjian, and J.P. Giroud [1997]. "Newmark Seismic Deformation Analysis for Composite Landfill Covers," Geotechnical News, September, pp. 22-25.

Matasovic, N. and E. Kavazanjian [1998]. "Cyclic Characterization of OII Landfill Solid Waste," Journal of Geotechnical and Environmental Engineering, ASCE, Vol. 124, No. GT3, March, pp. 197-1998.

Rathje, E.M. and J.D. Bray [2000]. "Nonlinear Coupled Seismic Sliding Analysis of Earth Structures," Journal of Geotechnical and Environmental Engineering, ASCE, Vol. 126, No. GT11, November, pp. 1002-1014.

Wong, C.P. and R.V. Whitman [1982]. "Seismic Analysis and Improved Seismic Design Procedure for Gravity Retaining Walls," Research Report 82-83, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.