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General Report — Session 7: Seismic Analysis and Design of Retaining and Marine Structures, Field Studies on Retaining Walls in California, Japan, and Around the World

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GENERAL REPORT - SESSION 7: SEISMIC ANALYSIS AND DESIGN OF RETAINING AND MARINE STRUCTURES, FIELD STUDIES ON RETAINING WALLS IN CALIFORNIA, JAPAN AND AROUND THE WORLD

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SUMMARY OF PAPERS

The twenty papers that were received for this session may be divided into five general topic areas. These topics along with the number of papers in each of the topic are as follows: (1) Rigid Walls with Dry Backfill - 9 Papers; (2) Rigid Walls with Saturated Backfill - 4 Papers; (3) Reinforced Earth Walls - 4 Papers; (4) Flexible Walls - 1 Paper; and (5) Dams and Slopes - 2 Papers. Brief summary of each of these papers are presented below.

Paper No. 7.02: "Critical Acceleration and Seismic Displacement of Vertical Gravity Walls by a Two Body Model," by C. A. Stamatopoulos and E. G. Velgaki (Greece).

The authors revisit the widely-used Mononobe-Okabe approach that is available to compute wall-soil interaction force under seismic conditions. They argued that the wall—backfill system in essence consists of two distinct bodies, each sliding along different inclinations. The backfill soil body slides along an inclined plane, while the wall slides along the wall-foundation soil interface. The paper first presented the equations of motions of these two bodies independently and described the solution technique that imposes the condition that there is no gap between the wall and the backfill. Using the principle of limit equilibrium, analytical expressions giving (1) the angle of slip plane in the backfill; and (2) the corresponding value of the critical acceleration; have been developed. The critical acceleration required by their approach has been compared to those estimated (by using iterations) by Richard-Elms solution and it was found to be the same. Subsequently the paper presented wall displacements computed using their method along with those computed using the Newmark's sliding block model (Richard-Elms method) under a variety of wall and soil parameters. The study revealed that the wall displacement computed by the new model is consistently lower, indicating that the Richard-Elms approach is conservative. The difference between the two displacements becomes negligible for large walls.

Paper No. 7.03: "Effects of Ground Improvement and Armored Embankment to the Displacements of the Seawalls and Backfill During Earthquake," by M. Kanatani, H. Tochigi, T. Kawai, and H. Ishikawa (Japan).

Based on large shaking table tests, the authors investigated the effects of the following three countermeasures against the displacements of caisson type seawalls during earthquakes: (1) armored embankment placed in front of the caisson; (2) densification of sandy seabed foundation just under the rubble mound; and (3) densification of backfill just behind the caisson. Five types of laboratory tests were conducted in which all of the above three countermeasures were modeled and responses were measured. The model tests were instrumented with accelerometers, pore pressure transducers, LVDTs, and earth pressure cells. The model tests were well documented and the results show that the first two countermeasures can significantly reduce the seaward displacement of the wall, while the third one is considerably effective to restrict the lateral deformation of the liquefied backfill even without the armored embankment in front of the caisson.

Paper No. 7.05: "Seismic Displacement of Rigid Walls – State of the Art," by Y. Wu and S. Prakash (USA).

Many design codes (e.g. AASHTO and Eurocode) specify the displacement-based approach as the rational method of design. They recommend the use of widely-used approaches (e.g. Richard and Elms and Whitman and Liao) which assume that the wall can only translate laterally away from the wall, without rocking. Many field observations and tests on centrifuge models have clearly revealed that walls resting on soil (flexible base) slide as well as rotate under seismic loading. The authors initially presented a summary of routinely used seismic displacement design approaches available for rigid retaining walls. They solve the coupled (sliding and rocking) dynamic equations of motion assuming that (1) the wall rotates about its heel and (2) the resistances from the foundation soil against sliding and rocking can be characterized by nonlinear springs. These spring parameters have been subsequently correlated to nonlinear shear modulus of the foundation soil. The numerical model developed by Wu (1994) has been used to compute wall displacement components (sliding and rocking) for a wall of height 4m subjected to a 1994 Northridge earthquake motion with a maximum acceleration of 0.344g. As many as seven different fields conditions have been assumed for the foundation and backfill. The study showed the importance of the rocking mode of deformation, in which the lateral wall deformation component due to rocking was substantially higher than those given for sliding. A surprising result was that the rocking deformation component was consistently higher by a more or less constant factor of 1.7 in all seven cases reported. The numerical model was also used to compare deformations recorded in a centrifuge test carried out on a rigid wall of prototype height 8m. The computed lateral wall displacement was about 31% higher than that was measured in the centrifuge.

Paper No. 7.06: "A Nummerical Study of Lateral Spreading Behind a Caisson-Type Quay Wall," by Z. Yang, A. Elgamal, T. Abdoun (USA), and C-J. Lee (China).

The paper reports on a series three centrifuge model tests conducted at RPI to study the seismic response of a caisson-type waterfront quay wall system. The backfill foundation soil consists of loose liquefiable cohesionless fine sand at 40% relative density. Different pore fluids were employed in the three tests, corresponding to a prototype permeability of 120 times, 60 times, and 1 times that of water, respectively. The centrifuge models were subjected to 20 cycles of roughly sinusoidal base excitation at a prototype frequency of 1 Hz, with an amplitude of 0.15g. Extensive instrumentation was deployed to record acceleration, displacement, excess pore pressure, and earth pressure on the wall. The base excitation resulted in liquefaction in the free-field within 2 to 3 cycles of excitation (Transducer P7). An accelerometer placed next to this transducer also clearly showed significant reduction ("decayed") in acceleration after two cycles of excitation. On the other hand, the pore pressure transducer located close to mid-height behind the wall did not show liquefaction. The accelerometer located underneath the wall also indicated no reduction in amplitude. The paper reported on the comparison of measured and computed responses. They used a finite element based computer program CYCLIC, which incorporated a material constitutive model specially developed for liquefaction analysis. The constitutive model is based on the multiple-yield-surface plasticity developed by Prevost (1985) for cohesionless materials. The comparison between the computed and measured responses was very good. A parametric study by varying soil permeability and relative density has also been reported. The study concluded that the dynamic properties and permeability of backfill are among the most controlling factors in dictating seismic performance of the quay wall system.

Paper No. 7.07: Seismic Response of Submerged Cohesionless Slopes, by G. Biondi, E. Cascone, and M. Maugeri (Italy).

Biondi et al. studied the seismic response of submerged cohesionless slopes. They made a point about the importance of not only the inertia effect of seismic force but also of the earthquake induced pore pressures on the seismic stability of the submerged slopes. They proposed a displacement analysis using an extension of Newmark sliding block model that takes into account the reduction in shear strength due to the pore pressure built-up along the potential sliding surface. In their analysis build-up of the pore pressure was evaluated using the simple pore pressure model based on the experimental data proposed by Coumoulos and Bouckovalas. Parametric analyses were performed in order to verify the effect of pore pressure build-up against the seismic slope response under a variety of excitation conditions with varying values of the soil relative density and different slope hydraulic conditions. From the analysis results, the authors demonstrated that ignoring the reduction of shear strength due to the pore pressure build-up may lead to a significant underestimation of the displacement, in particular for the case of loose sandy slopes. Furthermore, they propose the use of a simplified seismic stability chart to evaluate the maximum permanent seismic displacement of slopes.

Paper No. 7.09: "Seismic Active Earth Pressure Considering Effect of Strain Localization," by J-M. Zhang, and D. Li (China).

A new method based on pseudo-static and limiting equilibrium analysis has been proposed for evaluating seismic (static plus dynamic) active earth pressures induced by cohesionless backfills on rigid walls. The analysis is based on the well-known Mononobe-Okabe method; however, it attempts to account for the reduction in failure friction angle caused by deformation (residual friction angle) along the backfill slip plane. It is well documented that as deformation progresses, a reduction in friction angle occurs from a peak value to a residual value in dense sands. The reduction can be as much as 30%. The authors argue that the slip plane, which is consistent with the peak friction angle of the backfill, occurs initially in the backfill. However, subsequently as deformation continues, the friction angle on the same slip plane reduces to the residual friction angle. By reformulating Mononobe-Okabe approach based on this assumption, the authors developed new active seismic coefficients for design. As expected, the new values given by the authors fall between the corresponding Mononobe-Okabe values computed with residual and peak friction angles.

Paper No. 7.10: "Seismic Active and Passive Earth Pressures on Rigid Retaining Structures by a Kinematical Approach," by A-H. Soubra (France) and B. Macub (Slovenia)

Two new kinematically admissible failure mechanisms with rotational log-spiral slip surface have been proposed for evaluating the seismic active and passive earth pressures. Psuedo-static representation of earthquake effects (seismic coefficient concept) was adopted as in the Mononobe-Okabe analysis. The rigorous upper-bound solutions have been obtained utilizing the framework of the limit analysis. Numerical results of seismic active and passive earth pressure coefficients using the new approach have been computed and compared with other available solutions. The results showed that while the active coefficients computed by the proposed method are typically higher that those given by conventional methods, the passive coefficients are lower. The coefficients (active and passive) are presented in tabular form for ready use by engineers.

Paper No. 7.11: "A Field Study and Dynamic Finite Element Analysis of Railway Retaining Structures Damaged by the Hogoken-Nambu Earthquake (1995)," by Y. Nagayama, T. Matsui, I. Yasukawa, and H. Kasai (Japan).

Nagayama *et al.* reviewed the seismic damage to embankments and retaining walls caused by the Hogoken-Nambu earthquake. The work mainly falls into two parts: first, a statistical analysis of the damage in railway retaining structures, and second, a dynamic finite-element analysis. The statistical analysis was conducted for the following five types of damaged earth-retaining walls: gravity-type walls, leaning-type walls, embankments walls, geotextile reinforced earth walls, and reinforced-concrete walls. The degree of damage was divided into three categories: collapse, tilt, and crack. It was reported that damage to embankments, geo-textile reinforced-earth walls, and reinforced-concrete walls was less than the damage to gravity-type and leaning-type walls, when they are less than five meters. However, some leaning-type walls of height larger than 7 meters remained tilted without collapse. Damage to stone masonry walls with slope is twice than that for stone masonry walls without slope. In the case of embankment, the damage is proportional to the height of the embankment.

A two-dimensional finite-element analysis was then conducted for three different types of walls: gravity-type walls, leaning-type walls, and geo-textile reinforced earth walls. The soil properties obtained from the damaged sites of gravity-type walls were considered appropriate for all the three types of walls. Backfill soil and the top five-meter layer of the ground were modeled using the elasto-plastic Mohr-Coulomb's criterion. The soil below the top five-meter layer as well as the concrete wall was assumed linearly elastic. The results of the finite-element analysis showed that gravity-type walls develop delamination at the contact plane to backfill, whereas leaning-type wall developed sliding against the backfill. The geo-textile reinforced earth wall on the other hand developed tension in the reinforced material that prevented the wall from leaning or sliding.

Paper No. 7.12: "Dynamic Model Tests on Gravity Retaining Walls with Various Surcharge Conditions," by E. Cascone, A. S. L. Grasso, and M. Maugeri (Italy)

Shaking table tests have been conducted on gravity retaining walls with two different surcharge conditions: (1) a uniform surcharge on the entire surface of the backfill and (2) a uniform partial surcharge on the surface starting at a distance away from the top of the wall. The main objectives of these experiments were to investigate the effects of different surcharge conditions on the dynamic response of the soil-wall systems, the location of the potential failure surface formed in the backfill, and the seismic earth pressures. Another objective was to confirm the effectiveness of the equations proposed by Caltabiano et al. (1999) for the determination of seismic earth pressures against rigid walls with surcharge at a distant. The experimental results showed the following: (1) the soil-wall systems exhibited elastic response, before the input acceleration reached the system critical acceleration at which permanent displacements started to build up; (2) case of surcharge at a distance reduced the angle of the failure surface with respect to the horizontal and therefore led to a significantly increased seismic earth pressure; and (3) the test data are in good agreement with equations proposed by Caltabiano et al. (1999).

Paper No. 7.13: "Analytical Evaluation for Behavior of Shore Structures on Liquefied Area During Earthquakes," by K. Hayashi, T. Imono, T. Matsui, K. Oda, and H. Miyamoto (Japan).

The authors proposed a simplified method for predicting the residual displacements of the caisson of the quay wall during earthquakes. They divided the deformation analysis into 3 phases: (1) Phase 1 - before the earthquake, (2) Phase 2 - during the earthquake, and (3) Phase 3 - during liquefaction after the earthquake. The displacement component of the caisson at each phase was analyzed independently and the total displacement was estimated by summing up the displacements from each phase. In this analysis, evaluation of the "equivalent spring constants" becomes one of the important factors. Two sets of spring constants have been considered: K_p for the plastic condition and K_l for liquefied ground condition. These spring constants are obtained by reducing initial elastic spring constant K_e. The reduction factors were estimated based on the inverse analyses of the case histories of damaged sites. The authors recommended reduction factors of 0.003 for plastic condition and 0.025 for liquefied condition, respectively. In order to verify the applicability of the prediction of the residual displacement of the caisson, the results from the proposed simplified method were compared against those computed from a dynamic response analysis using the program FLIP, which is based on the effective stress characterization for soil. The residual horizontal displacements by both analyses without liquefaction of the ground showed a similar trend, while those cases with liquefaction showed noticeable variation.

Paper No. 7.14: "Seismic Analysis and Retrofit of Dock Walls," by A J Mair and D M. Wood (UK).

The paper presented results of an extensive numerical analyses that have been undertaken to assess the seismic performance of old dock walls under earthquake loading. Study also explored appropriate remedial measures that could be undertaken to improve the seismic performance. The computer program FLAC in time domain was utilized in the analyses reported. Fills were modeled as elasto-plastic Mohr-Coulomb frictional materials, while concrete elements were assumed elastic. The analysis also included interface elements. The results computed using the program FLAC were demonstrated by comparing responses from three specific examples of dock walls with and without retrofits. Retrofit measures such as anchors, tension piles, and counterforts have been considered. The study also showed the interface representing construction joints or masonry bedding has an important influence on the predicted earthquake response.

Paper No. 7.15: "Seismic Analysis of Bridge Abutments: A Numerical Simulation of a Field Load Test," by L. Yan and G. R. Martin (USA).

Bridge abutment stiffnesses and capacity play an important role in the computer modeling of bridge structures. The study used an experimental study conducted at the University of California, Davis (UCD) in which passive resistance and lateral stiffness of a bridge abutment were measured. In this experimental study, one test was a displacement controlled lateral (longitudinal) cyclic loading test of a half-scale abutment (West Abutment). The abutment was provided with a structural fill (well graded silty sand) adjacent to the wall and the embankment being supported consisted of a low plasticity clayey silt known as "Yolo Loam." A thin drainage layer of pea gravel was placed between the wall and the structural backfill. The abutment under investigation was supported on three reinforced concrete piles. The measured response showed that the lateral secant stiffness reduced by as much as a factor 5 over a wall displacement of 3 inches.

The paper presented results of a numerical simulation of the field test using the computer program FLAC. In the numerical model the abutment was represented as a rigid body, while the soils (structural backfill, pea gravel, and embankment soil) were represented using a plastic model with multiple yield surfaces (MYC). Interface elements were used between the structural fill and the pea gravel and also between the pea gravel and the wall. The study showed that the FLAC model successfully simulated the measured abutment behavior. The comparison between the computed and measured secant stiffnesses of the abutment was very good.

Paper No. 7.18: "Investigation of Seismic Response of Reinforced Soil Retaining Walls" by K. Hatami and R. J. Bathurst (Canada).

Seismic deformation response of a segmental (modular block) retaining wall of 3.6m height to recorded and harmonic ground excitations using a numerical model has been presented. The wall response is presented in terms of lateral displacement histories of the wall facing and maximum value of seismically-induced incremental load on the reinforcements. As many as eight excitation histories, of which six were recorded motions, and two were harmonic motions. All the motions were scaled to yield a maximum acceleration of 0.15g. The computer program FLAC, which is capable of computing the wall response under both the initial static (prior to earthquake) and dynamic (excitation) loading conditions has been used to compute the wall response. A nonlinear incremental analysis along with an appropriate constitutive relationship of the type proposed by Duncan et al. (1984) has been adopted with FLAC runs. The displacement responses of the wall under study (height 3.6m) subjected to harmonic input were considerably higher than those computed with real earthquake records, even though they had comparable predominant frequencies. This led to a conclusion by the authors that care should be exercised when interpreting displacement behavior of walls based on their performance under harmonic excitations. The authors suggested that the random characteristics of actual ground motions may be the reason for the documented good performance of reinforced-soil retaining walls in the past earthquakes.

Paper 7.19: "Stability Analysis of the Geosynthetic-Reinforced Modular Block Walls Damaged During the Chi-Chi Earthquake," by C. C. Huang (China) and F. Tatsuoka (Japan).

Post earthquake damage reports after the 1999 Chi-Chi earthquake in Taiwan revealed that three geosynthetic-reinforced walls located at about 40km from the epicenter suffered noticeable damage. Among the walls reported, one completely collapsed. The sites where the walls were located experienced a maximum acceleration in the order of 0.44g from the earthquake. The heights of damaged walls were similar and they varied between 2.7 and 3.2m. Psuedo-static stability analysis based on Coulomb's "one wedge" and "two wedge" methods were made for the two walls that behaved very differently in this earthquake. The performance of these walls has been partially explained based on the psuedo-static stability analysis. Two-wedge failure mechanism is shown to be a dominant one for the walls investigated. The study showed that the seismic stability of the reinforced wall depends on the connection strength between the geogrids and the facing.

Paper No. 7.20: "Evaluation of Seismic Safety of a Large Caisson Structure," by T. Matsui, I. Aoshima, A. Nakahira, C. Kuroda, K. Oda, H. Murakami, and N. Suzuki (Japan).

Matsui et al. investigated the seismic safety of a large caisson foundation of the Aji-River gate, Japan resting on a multi-layered clay foundation to level 2 earthquakes. First, the seismic interaction between the soil layers and the large caisson foundation was elucidated by means of centrifugal shaking tests, where the model was approximated as a two-dimensional model made of aluminum scaled to 1/75 of prototype. The model was subjected to an actual seismic excitation with a maximum amplitude of 0.2g.

This was followed by a two-dimensional seismic effective stress based finite-element analysis of the prototype. The caisson was modeled using two-dimensional plane strain finite elements and was assumed linear elastic. The stress-strain relationship for the soil layers was represented by the Ramberg-Osgood model with the shearing strain-dilatancy relationship represented by Bowel model. Good results were reported between the finite-element predictions and the measured responses.

The finite-element analysis was then used to evaluate the seismic safety of the Aji River tide gate. On the basis of model failure tests on reinforced concrete members of caissons, the concentrated damaged parts of caissons were modeled by tri-linear beam elements. The model was subjected to ground motions corresponding to level 2 earthquakes. The results reported by the authors showed that the caisson foundation had enough seismic safety against the flexural and shearing failure.

Paper No. 7.22: "On the Seismic Earth Pressure Reduction Against Retaining Structures Using Lightweight Geofoam Fill," by H. Hazarika, J. Nakazawa, H. Matsuzawa (Japan), and D. Negussy (USA).

Hazarika et al. carried out two-dimensional finite-element analyses for a rigid retaining wall subjected to sinusoidal as well as realistic earthquake loadings. The aim was to investigate the effect of replacing the granular backfill partially with lightweight expanded polystyrene geofoam on the exerted seismic thrust on the structure. The motivation for this work was the observation that retaining structures with lightweight expanded polystyrene geofoam behaved well without serious damage, when compared with retaining structures having granular backfill.

In the two-dimensional finite-element analysis the wall was assumed rigid, supporting dry cohesionless backfill. The wall was modeled as either restrained (i.e. non-yielding) or allowed to move (i.e. yielding). The model was subjected to two types of ground accelerations: (1) sinusoidal, and (2) a recorded earthquake motion from the Hyogoken-Nanbu earthquake. The analysis was first preformed using the sandy backfill alone in order to determine the extent of the failure zone in the backfill. This zone was then substituted by the lightweight expanded polystyrene geofoam, and the analysis was repeated. The sandy backfill was modeled using a localization based constitutive model, whereas the lightweight expanded polystyrene geofoam was modeled using the elasto-plastic Drucker-Pragar model. Interface elements were used between the backfill and the wall. The results showed that the use of lightweight expanded polystyrene geofoam as a replacement reduced the seismic thrust by about 50%.

Paper No. 7.24: "Evaluation of a Soldier Pile-Tieback Wall at Carquinez Bridge," by M. Momenzadeh and K. Jackura (USA).

The authors reported on a simplified static and dynamic soil-pile-tendon interaction analysis using the program MBC76P. The wall under study was 21m in height and was designed based on the procedure recommended in 1990 Caltrans Memo 5-12 to Designers using static loading conditions. The seismic load increments were evaluated using the Mononobe-Okabe relationship along with a horizontal acceleration coefficient of 0.35. This acceleration coefficient was derived from the seismic risk assessment at the site. The study indicated that the application of seismic earth pressure increment mobilized the reserve loading carrying capacity of the wall system and resulted in quantifiable wall deformations. The authors pointed to two sources of reserve capacity that normally exists in wall systems. One is due to tendon stretch and the other due to pile resistance offered by the piles extending below the slide surface. The study concluded that these factors in a stable, flexible wall system can accommodate substantially increased load with acceptable wall deformations.

Paper No. 7.30: "Seismic Analysis of a Partially-Buried Drinking Water Reservoir," by S.T. Srithar (Australia) and U. D. Athukorala (Canada).

The authors conducted a seismic soil-structure-fluid interaction analysis in order to more realistically predict the seismic response of the perimeter walls of a partially-buried drinking water reservoir. Two-dimensional finite element program FLUSH, which is based on the equivalent linear method, was employed to undertake the seismic response analysis. The structural components of the reservoir such as the wall, footings, and the concrete liner were modeled using linear bending beam elements. Hydrodynamic effects and convective sloshing forces resulting from the water contained in the reservoir have been accounted for. This was achieved by modeling a series of equivalent lumped masses and a spring attached to selected nodes of the wall. A comparative case study has been reported involving the following two cases: (a) reservoir with the design high water level and with the hydrodynamic effects and (2) reservoir with the design low water level but without the hydrodynamic effects. By comparing the maximum seismic lateral earth pressure, bending moment, and shear force in the wall between the two analyses, they demonstrated the importance of the hydrodynamic effects on the stability of the reservoir.

Paper No. 7.31: "A Case History: Seismic Analysis of Retaining Wall of the "Sacro Convento" in Assisi," by T. Crepellani, C. Madiai, and G. Vannucchi (Italy).

Crespellani et al. investigated the seismic behavior of the "Sostruzione" retaining wall of the "Sacro Convento" in Italy, which was hit by a series of earthquakes in 1997. Three earthquakes with peak ground acceleration exceeding 0.15g recorded at a nearby location were selected as base input in the analyses. The geotechnical investigation at the site consisted of 12 boreholes extended to depths varying between 5m and 22m. Three different types of analysis were conducted: static, pseudo-static, and dynamic. The analyses were performed by assuming a two-dimensional geometry.

The static component of the total active earth pressures was applied at an elevation of one-third of the wall height, and the total seismic earth pressure increment was applied at two-third the wall height. A pseudo-static analysis was performed following the Italian seismic code assuming a 2nd category seismic zone. The dynamic analysis was undertaken by numerically integrating the translational and rotational equations of motion. The seismic input was assumed to be uniform along the height of the wall.

The authors conducted static stability analyses in both translation and rotation and found the structure to be safe. The pseudo-static stability analysis in translation was safe for all the sections studied, whereas in rotation, the stability was adequate for one section only. The results obtained from the dynamic analysis were not in good agreement with their measured counterparts. The authors attributed such discrepancy to the unknown deformation from previous earthquakes, and to the two-dimensional approximation of the wall.

Paper No. 7.33: "Displacement-Based Design Criteria for Gravity Retaining Wall," by D. Wotring and G. Andersen (USA).

The Richards-Elms (1979) procedure of displacement based design of retaining walls used the statistical analysis of earthquake records conducted by Franklin and Chang (1977) to arrive at the displacement upper bound for design. The authors report a preliminary investigation of digitized excitation records from Loma Prieta, Northridge, and Kobe (in all 8 records) and showed that the Richard-Elms upper bound curve for displacement leads to significantly lower wall displacement. Consequently, this means that walls designed with the Richards-Elms procedure will be unconservative. An upper bound developed from Northridge data results in as much as 25% increase in required wall weight above those computed with Richards-Elms procedure. The analysis involving integration of seismograms of recent earthquakes carried out by the authors suggested that the normalizing parameters of peak velocity and peak acceleration (as suggested by Richards-Elms) may not be sufficient to arrive at a conservative wall design.