Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (41) No. (3) July, 2019

Numerical Simulation of Centrifuge Test Results on Retaining Wall using the Finite Difference Method

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ملخص

بناءً علي نتائج مستخلصة من اختبار طرد مركزي، تمت دراسة السلوك الزلزالي للحوائط الساندة المقيدة المقامة في تربة جافة غير متماسكة. وباستخدام طريقة الفروق المحددة تم بناء نموذج عددي بهدف محاكاة اختبار الطرد المركزي. مثلت القراءات المسجلة أثناء زلزال لوما بريتا عام 1989 مصدر التأثير الزلزالي، وقد تم التأثير بها علي الحد السفلي لكلاً من اختبار الطرد المركزي والنموذج العددي، ويقع الحد المشار اليه علي عمق 13 متراً أسفل قاعدة الحائط الساند محل الدراسة. تم استخدام النتائج المقاسة أثناء الاختبار بهدف معايرة وتأكيد النتائج المستخلصة من النموذج العددي. وقد وجد أن ضغط التربة الزلزالي الجانبي المحسوب يتوافق بصورة كبيرة مع النتائج المقاسة معملياً. تم حساب قيم الدفع الزلزالي وعزوم الانحناء الناتجة من النموذج العددي ومقارنتها مع بعض الطرق المعروفة. أظهرت النتائج التأثير الواضح لجساءة الحائط و السلوك غير الخطي للتربة علي السلوك الزلزالي للحوائط الساندة المقيدة.

Abstract

The available results from a centrifuge test were utilized to investigate the seismic behavior of restrained (non-yielding) retaining walls in dry cohesionless soils. A numerical model was developed using the finite difference method to simulate the centrifuge test configuration. The records of Loma Prieta earthquake in 1989 were utilized as a source of seismic excitation, and were applied at the lower boundary of both the centrifuge and numerical models, located at a depth of 13 m below the bottom of the retaining walls. The available seismic earth pressure measurements were used to calibrate and validate the numerical model results. The predicted seismic earth pressure was in good agreement with the measured values. The seismic thrust and bending moment on the retaining wall were calculated and compared with some well-established methods in the literature. The results emphasize the significant effect of wall stiffness and soil nonlinearity on the seismic behavior of restrained retaining walls.

Keywords

Centrifuge modelling; nonlinear dynamic model; restrained retaining walls; seismic earth pressure; seismic thrust; wall stiffness

1. Introduction

The seismic pressure on retaining walls has been the subject of considerable geotechnical research in the last few decades. This is attributed to the increased interest in understanding and evaluating the seismic behavior of retaining walls. The M-O method [1] is a well-established method to calculate the seismic forces on yielding retaining walls. However, the seismic earth pressure on restrained (non-yielding) retaining walls cannot be determined from the M-O method in absence of free wall movement. Wood [2] calculated the dynamic thrust and bending moment on a rigid wall retaining dry cohesionless soil. However, the soil behavior was assumed linear elastic, and the wall was considered infinitely rigid. Accordingly, the resulting seismic thrust and seismic bending moments on the wall were too high.

Therefore, there is a need to focus on the seismic behavior of restrained (non-yielding) retaining walls. Many researchers investigated the seismic behavior of restrained retaining walls in the laboratory using the shaking table or the centrifuge model ([3] - [8]). However, the results of these model tests, despite being a true representation of actual behavior, remain exclusively applicable to the tested configuration and may not be reliably applied to different configurations.

In this study, the results of a centrifuge model test on restrained retaining walls are utilized to develop a numerical model that simulates the seismic interaction between the wall and the surrounding dry sand. The numerical model is based on the finite difference method, and a nonlinear dynamic model is adopted for the dry sand behind the retaining walls and underneath the raft. The results of the centrifuge test were utilized to calibrate and validate the numerical model, which will be used in further studies to investigate the seismic behavior of restrained retaining walls like basement walls, abutments and culverts.

The available measurements from the 1989 Loma Prieta earthquake were used in the centrifuge model and, hence, were utilized in the numerical model. The acceleration-time history of Loma Prieta earthquake is shown in Figure 1. The acceleration-time history was applied at the lower boundary of the numerical model. The peak acceleration was 0.41g, and the earthquake duration was 53 sec.

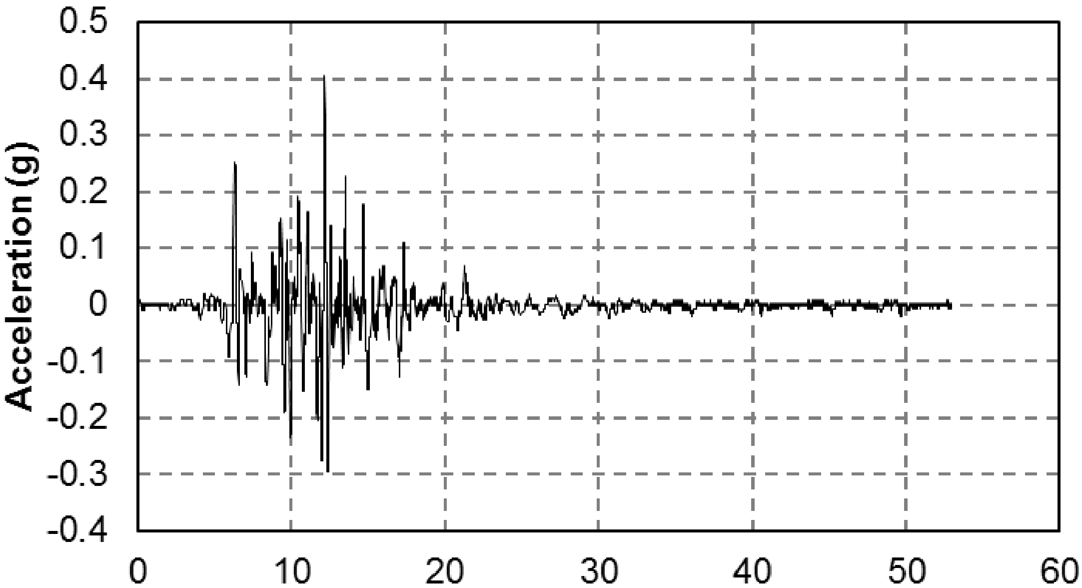

Figure 1: Acceleration-time history for the earthquake used in the centrifuge test and numerical simulations (modified after Mikola [7])

2. Centrifuge Testing

A centrifuge model for restrained walls retaining dry sand was developed by Mikola [7] in order to model their seismic interaction. Figure 2 and Figure 3 show the centrifuge model configuration. The walls on the left side represent stiff braced walls, while the walls on the right side represent flexible braced walls. The retaining walls were restrained at top by struts or props, and were connected at the bottom by raft slabs. The seismic excitation, represented by the time history shown in Figure 1, was applied at the lower boundary, located at a depth of 13 m below the bottom of raft. Mikola [7] installed load cells to calculate the seismic thrust forces. Hence, the seismic earth pressures could be determined.

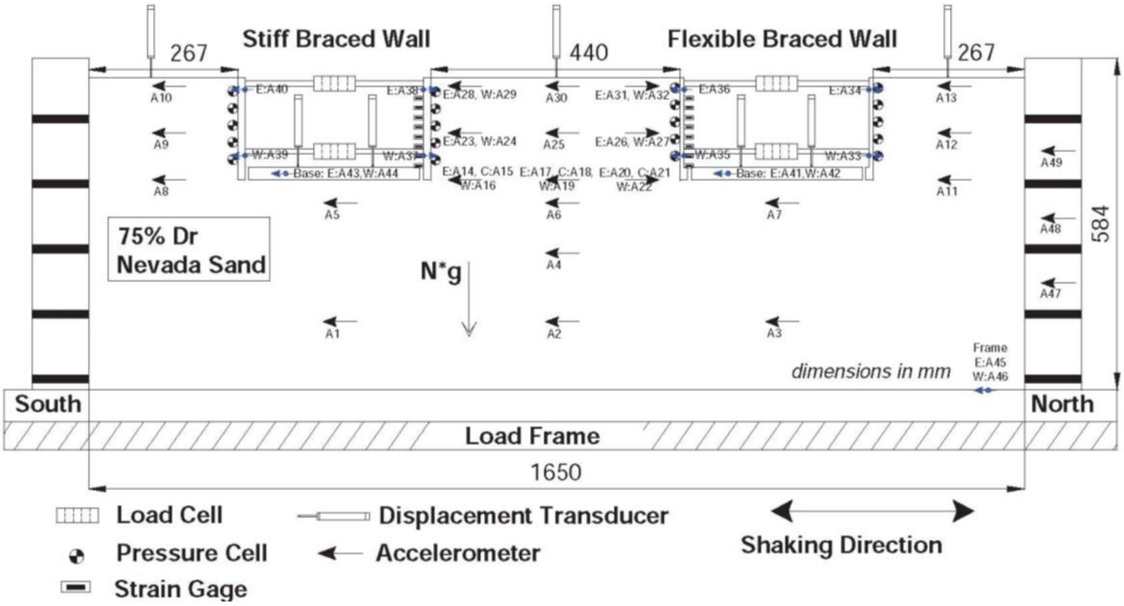

Figure 2: Configuration of the centrifuge model (after Mikola [7])

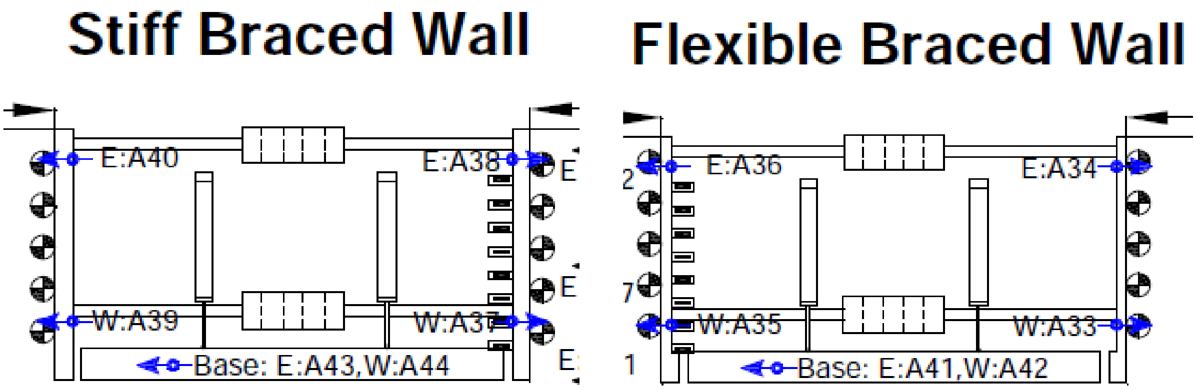

Figure 3: Close-up view of stiff and flexible walls from the configuration of the centrifuge model (after Mikola [7])

The retaining walls were underlain by dry sand, which was also used for backfilling behind the walls. Table 1 shows the geotechnical properties of the sand (Mikola [7]). A reference maximum shear modulus (G_{ref}) of 150 MPa was considered to correspond to a mean effective stress (p') of 100 kPa. Equation (1) was used by Mikola [7] to determine the maximum shear modulus.

$$G_{\max} = G_{ref}\left(\frac{p'}{p_A}\right)^{0.5} \quad \text{[1]}$$

Where p_A is the atmospheric pressure

Table 1: Geotechnical properties of Sand (after Mikola [7])

Property	Value
Unit weight (kN/m^3)	16.95
Internal friction angle (degrees)	35
Reference maximum shear modulus (MPa)	150
Relative density (%)	75

3. Numerical Modeling of Centrifuge Results

In this paper, a numerical model is developed to simulate the seismic interaction between restrained retaining walls and dry cohesionless soils using the centrifuge test results. The main objective is to calibrate and validate the numerical model in order to provide a reliable numerical prediction of the seismic behavior of restrained retaining walls. This paper focuses on the results of the numerical model calibration/validation.

The numerical model is based on the finite difference method, and the simulations are carried out using the finite-difference-based software FLAC 7.0 (Fast Lagrangian Analysis of Continua). The numerical model simulates the nonlinear behavior of soil during static and seismic conditions. The fully nonlinear analysis allows the numerical model to follow the prescribed nonlinear constitutive relationship in an accurate way and without the need for iterations as in the equivalent linear method.

Figure 4 and Figure 5 show the configuration of the finite difference mesh used in the analysis. The numerical model allows for defining quiet boundaries, which serve as absorbing boundaries for the propagated seismic waves, thereby preventing radiation of seismic waves from the lateral boundaries back to the structure. This feature of the program helps reducing the mesh size by avoiding increasing the distance to lateral boundaries. Hence, considerable computation time can be saved.

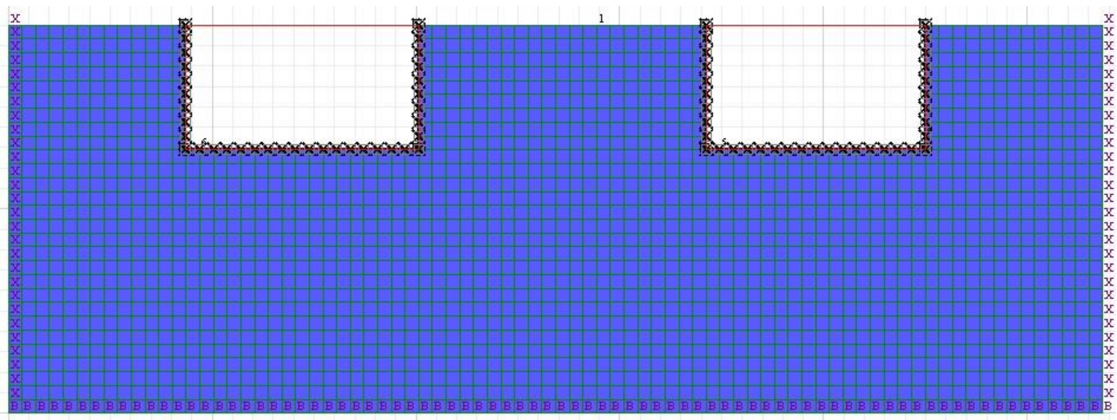

Figure 4: Configuration of the finite difference mesh

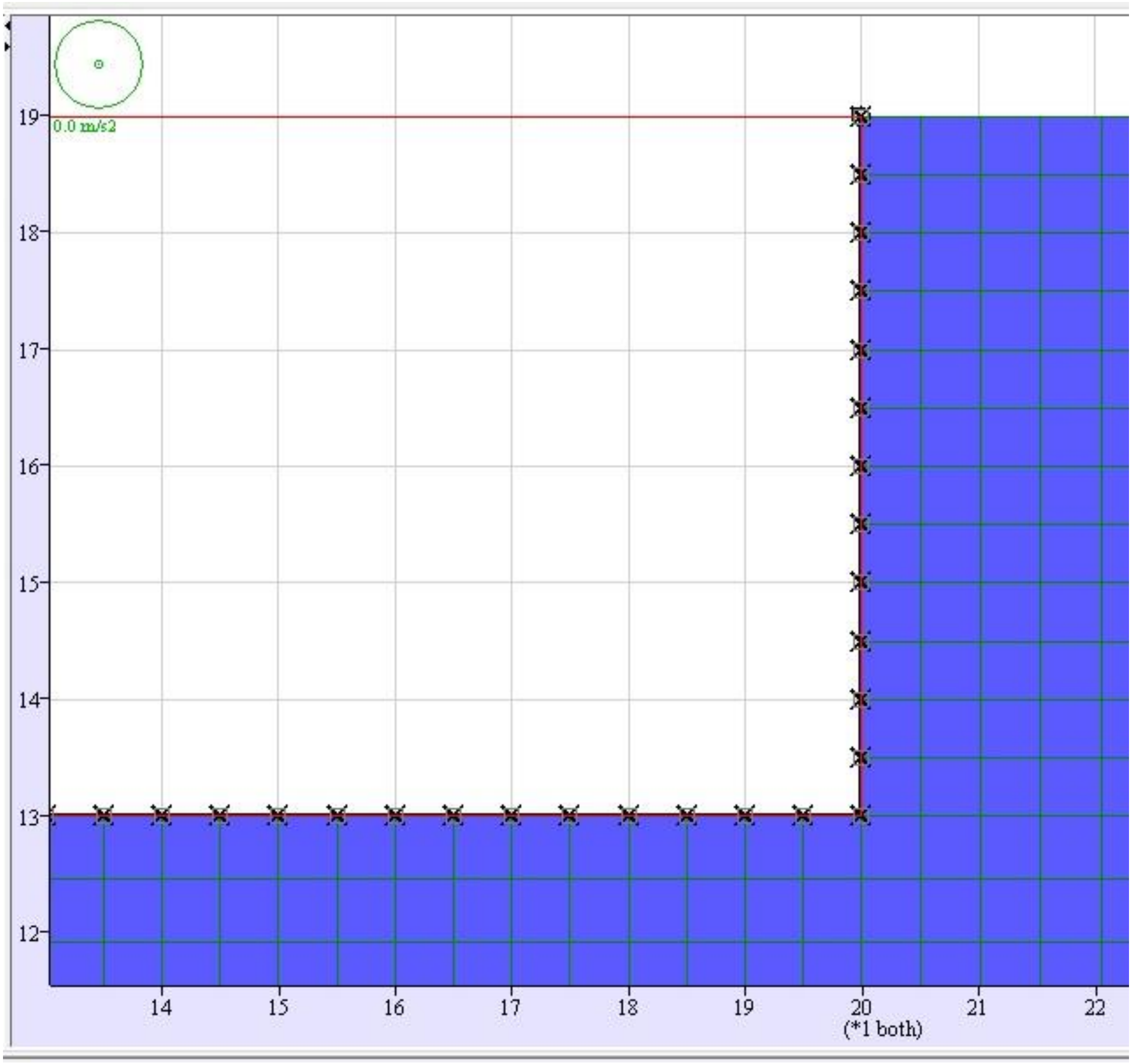

Figure 5: Close-up view of the finite difference mesh around the retaining wall

Static stress deformation analysis was carried out to calculate the stress deformation state in the ground due to gravity forces before excavation, and after excavation and construction of the retaining walls, lower rafts and upper struts. The static analyses were followed by seismic analysis to simulate the effect of seismic excitation by applying the acceleration time history.

The nonlinear dynamic model developed by Byrne [9] was employed to simulate the constitutive behavior of dry sand behind the retaining walls and underneath the rafts. Byrne [9] developed a two-parameter model to calculate the incremental volumetric strain per each cycle of shear strain in terms of the accumulated volumetric strain from previous loading cycles, the amplitude of shear strain for the loading cycle under consideration, and two parameters determined based on the relative density of sand.

4. Analysis of Results

The numerical analysis results are interpreted in terms of the induced seismic earth pressure during the earthquake. As mentioned in Section 2, the resultant (static plus seismic) earth pressure was measured using load cells installed by Mikola [7].

Figure 6 shows the predicted resultant (static plus seismic) earth pressure from the numerical model. The figure also shows the measured static plus seismic earth pressure from the centrifuge test at a depth of 0.5 times the wall height (6.0 m). The results indicate that the numerical model can reasonably predict the peak and residual resultant earth pressures.

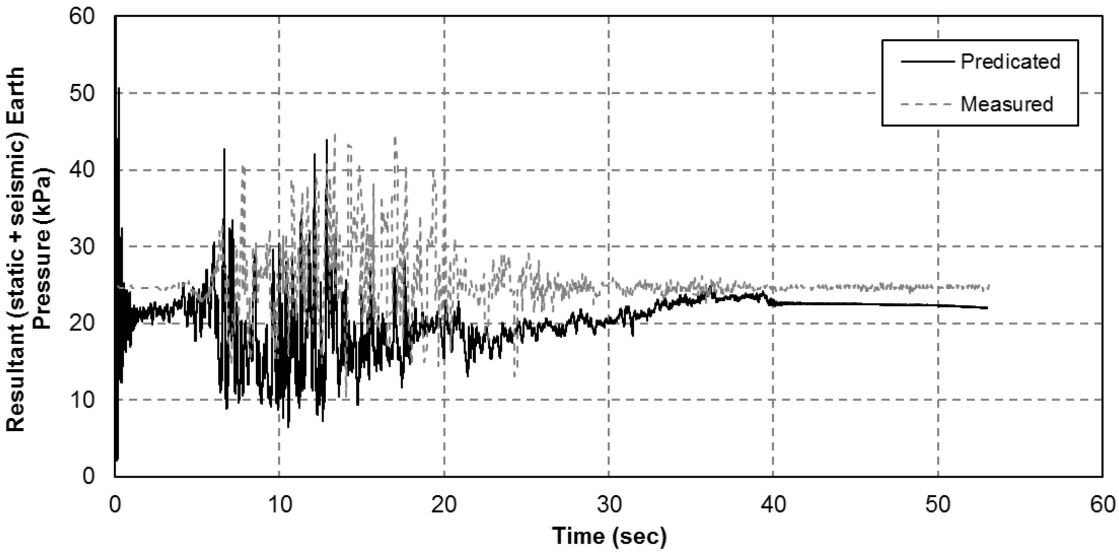

Figure 6: Measured and predicted total (static plus seismic) earth pressure at a depth of 0.5 times the wall height

Figure 7 shows the maximum earth pressure envelope (maximum-maximum values) constructed by calculating the maximum resultant earth pressure from the numerical model results at different depths along the wall height. The corresponding resultant thrust on the wall was 276 kN. This value represents the sum of static and seismic thrust forces. The static thrust was calculated from the numerical model from the stage corresponding to static conditions before applying the seismic excitation. Accordingly, the net thrust due to seismic forces was equal to 184 kN. The numerical model results were compared with the equations developed by Wood [2], where the seismic thrust (ΔP_{EQ}) can be calculated using the following equation:

$$\Delta P_{EQ} = \gamma H^2 \frac{a_h}{g} F_p \quad \text{[3]}$$

Where;

γ is the unit weight of soil behind the wall;

H is the wall height;

a_h is the peak horizontal seismic acceleration;

g is the gravity acceleration; and

F_p is a unitless factor that depends on the extent of the backfill behind the wall and Poisson's ratio

For an infinite backfill behind a retaining wall and a Poisson's ratio of 0.3 (typical to sands), the factor *Fp* can be taken equal to 1.0. Therefore, the seismic thrust is equal to 294 kN according to Wood [2] equation.

Similarly, the resultant (static plus seismic) bending moment envelope was extracted from the numerical model and compared with the equation developed by Wood [2]. The predicted resultant (static plus seismic) bending moment envelope is shown in **Figure 8**. The maximum bending moment equals 420 kN.m/m'. This value represents the sum of maximum static and seismic bending moments. The maximum static bending moment was also extracted from the numerical model. Hence, the predicted maximum seismic bending moment equals 350 kN.m/m'.

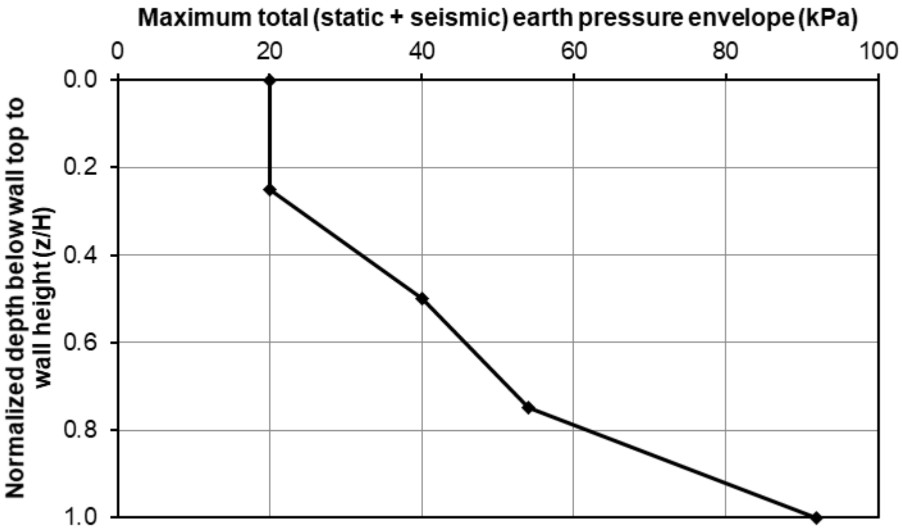

Figure 7: Maximum total (static plus seismic) earth pressure envelope along the wall height

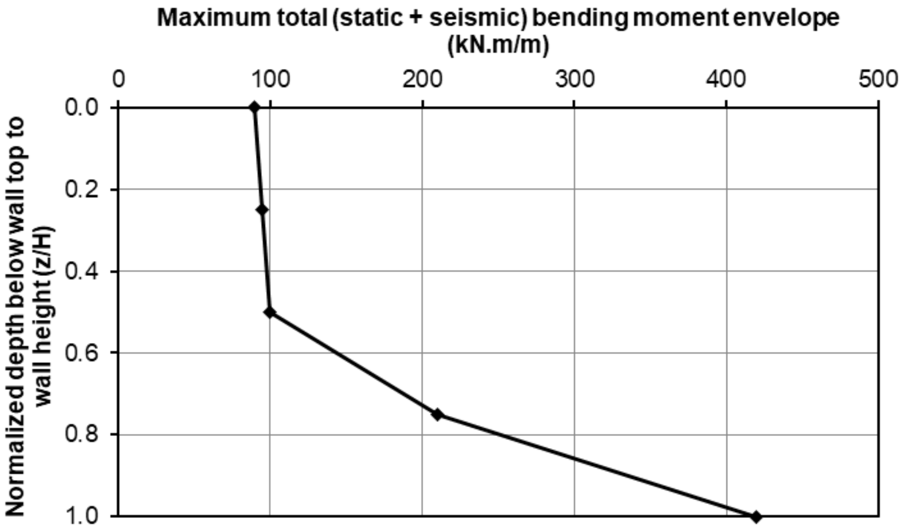

Figure 8: Maximum total (static plus seismic) bending moment envelope along the wall height

On the other hand, Wood [2] expressed the maximum seismic bending moment (ΔM_{EQ}) using the following equation:

$$\Delta M_{EQ} = \gamma H^3 \frac{a_h}{g} F_m \quad \text{[4]}$$

F_M is a unitless factor that depends on the extent of the backfill behind the wall and Poisson's ratio. For an infinite backfill behind a retaining wall and a Poisson's ratio of 0.3 (typical to sands), the factor F_M can be taken equal to 0.54. Therefore, the maximum seismic bending moment equals 1,031 kN.m/m' according to Wood [2] equation.

These results indicate that Wood [2] significantly overestimated both the seismic thrust force and seismic bending moment. This overestimation of seismic thrust and bending moments can be attributed to the following:

- Wood [2] assumed an infinitely rigid wall. However, retaining walls are usually restrained at certain points along its entire height. Therefore, they are neither yielding nor completely non-yielding. For the case analyzed in this study, the retaining wall is restrained at top and bottom, but is relatively free to move at the middle and towards the two ends. Moreover, the retaining wall has actually a finite thickness, so it cannot be considered infinitely rigid.
- Wood [2] assumed a linear elastic behavior of the soil behind the wall. The actual soil behavior under seismic loads is essentially nonlinear where the modulus is reduced and the damping ratio is increased with increasing the cyclic shear strain amplitude. These aspects of dynamic soil behavior are not captured in linear elastic constitutive models.
- Wood [2] adopted the pseudo-static approach by considering inertial forces corresponding to the peak acceleration. In actual earthquakes, however, the peak acceleration is not applicable over the total duration of the earthquake.

5. Conclusions

The conclusions of the conducted study can be summarized in the following points:

- The finite difference method is a powerful tool to simulate the seismic interaction between non-yielding (restrained) retaining walls and surrounding soil.
- The seismic behavior of restrained retaining walls is a sophisticated problem that cannot be idealized by simple pseudo static conditions or using empirical procedures.
- Soil nonlinearity has a pronounced effect on the seismic interaction with restrained retaining walls. Empirical methods based on the assumption of a linear elastic soil medium (e.g. Wood [2]) yield very high seismic bending moments leading to an overly conservative design.

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