NUMERICAL INVESTIGATION OF GEOFOAM SEISMIC BUFFERS USING FLAC

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ABSTRACT

The paper describes the development and verification of a FLAC numerical code that was used to simulate the results of an experimental program of reduced-scale wall models with a seismic geofoam buffer inclusion using a large shaking table. Two physical tests constructed with EPS geofoam materials having different modulus values and a control case with no geofoam inclusion were simulated. The paper shows that the numerical model was able to capture the trend in earth forces with increasing base acceleration for all three models. The numerical simulation results are also shown to be in quantitative agreement with the relative reduction of the earthquake-induced dynamic earth forces generated against the rigid wall structures with an EPS geofoam seismic buffer compared to the control case without seismic protection.

INTRODUCTION

In a companion paper by Zarnani et al. (2005) the concept of reducing earth forces against rigid wall structures by placing a compressible vertical inclusion between a rigid wall and the backfill was reviewed for the cases of static and earthquake loading. The proof of concept has been demonstrated for the static case from the results of small-scale laboratory tests (McGown and Andrawes 1987, McGown et al. 1988) and a monitored field installation (Partos and Kazaniwsky 1987). Physical shaking table tests demonstrating that the same approach can be used to reduce the potentially much larger seismic-induced forces during earthquake have been reported by Hazarika et al. (2003) and Zarnani et al. (2005). Both studies used a vertical inclusion of expanded polystyrene (EPS) geofoam as the compressible layer. They demonstrated that the peak lateral loads acting on the compressible model walls during simulated earthquake loading were reduced to as much as 60% of the value measured for the nominally identical structure but with no compressible inclusion. Inglis et al. (1996) reported the first documented field installation of a rigid basement wall constructed with a compressible EPS geofoam layer for the purpose of seismic-induced earth load reduction. The design of the structure was carried out using the program FLAC. The results of numerical modeling predicted that a 1-m wide layer of EPS geofoam placed between a 10 m-high wall and granular backfill could reduce lateral loads during an earthquake event by 50% compared to the unprotected wall option.

Parametric studies using a FEM code to model rigid wall structures with a compressible inclusion have been reported in the literature for the static loading case by Karpurapu and Bathurst (1992). Their FEM program was first verified against the physical model tests reported by McGown and Andrawes (1987) and McGown et al. (1988) and then used to generate design charts. The design charts can be used to select the combination of geofoam buffer thickness and modulus required for different combinations of wall height and granular backfill soils to
minimize static earth forces. In addition to the work of Inglis et al. (1996), other numerical modeling studies of the seismic geofoam buffer concept have been reported by Pelekis et al. (2000), Hazarika (2001), Hazarika and Okuzono (2002) and Armstrong and Alfaro (2003). However, none of numerical models developed by these researchers have been verified against instrumented physical test results. Hence, while qualitative trends in the numerical predictions may appear reasonable, confidence in the magnitude of numerical results must be accepted with caution.

In this study, a numerical model using the program FLAC is described that was used to simulate the dynamic response of 1 m-high reduced-scale models of rigid walls with and without a geofoam seismic buffer. The physical tests were carried out on a shaking table at the Royal Military College of Canada. The physical test program and example test results are described in the companion paper by Zarnani et al. (2005). These carefully conducted and instrumented physical tests provide a useful dataset for verification of the numerical model.

**RMC SHAKING TABLE TESTS**

A brief description of the RMC shaking table tests is described here for completeness. One meter-high by 1.4 m-wide by 2 m-long models were constructed in a strong box bolted to a large steel shaking table. A rigid wall constructed from a stiffened aluminum bulkhead was attached to the shaking table platform and used to retain a synthetic granular soil. The rigid wall was attached to load cells to record total horizontal and vertical loads transmitted to the wall at end of construction and during subsequent horizontal shaking. Accelerometers were also installed to record accelerations recorded at the wall boundary and within the backfill. A geofoam buffer 150 mm thick was placed between the rigid wall and the backfill. A control test without the geofoam seismic buffer was also carried out to quantify the performance benefit due to the presence of the geofoam buffer to reduce dynamic loads on the rigid wall. Potentiometer-type displacement devices were mounted on the front of the rigid wall to record the horizontal movements of small metal plates attached to the geofoam-sand interface. A stepped-amplitude sinusoidal acceleration record with a frequency of 5 Hz was applied to the base of the models in all tests. The acceleration amplitude was increased at 5-second intervals (0.05g increments) up to peak base acceleration amplitude in excess of 0.8g and the test terminated.

**NUMERICAL MODELS**

The numerical simulations were carried out using the program FLAC (Itasca 2005). The FLAC numerical grid for the simulation of the geofoam buffer tests is shown in Figure 1. The height of each model and the backfill width were kept at 1 m and 2 m, respectively in all tests. The thickness of the geofoam was taken as 150 mm to match the physical tests. In this investigation, the results of two numerical simulations with two different geofoam densities are reported together with a control test without the geofoam buffer. The results of simulation runs are compared to the results from the corresponding tests in the physical test program.

The backfill soil was modeled as a purely frictional, elastic-plastic material with Mohr-Coulomb failure criterion. This model allows elastic behavior up to yield (Mohr-Coulomb yield point defined by the friction angle), and plastic flow at post-yield under constant stress. The soil
model is described by constant values of shear and bulk elastic modulus for pre-yield behavior. The results of direct shear box tests on specimens of the same sand material have been reported by El-Emam and Bathurst (2004, 2005) and are summarized in Table 1. They also carried out numerical simulations of the direct shear tests using a FLAC code to back-calculate the peak plane strain friction angle of the soil and modulus values. The peak plane strain angle from the shear box simulations was $\phi_{ps} = 58^\circ$, which is consistent with the value predicted using the equation by Bolton (1986) to convert the peak friction angle from conventional direct shear box tests to plane strain conditions. The soil properties for the backfill sand used in the numerical analyses are also summarized in Table 1.

The geofoam buffer material was modeled as a linear elastic, purely cohesive material. The elastic properties of EPS geofoam have been shown to vary linearly with EPS density. A relationship proposed by Horvath (1995) was used to calculate the elastic modulus of the two EPS materials (and hence the bulk and shear modulus values). While a more advanced non-linear strain hardening model could have been implemented in the FLAC code, the simple constitutive model adopted here was judged to be sufficient since the measured compressive strains in the physical models were less than the elastic strain limit of 1% determined from rapid uniaxial compression tests reported by the manufacturer (BASF 1997). The elastic properties assumed for the geofoam materials in this investigation are shown in Table 2.

A no-slip boundary at the bottom of the sand backfill was assumed to simulate the rough boundary in the physical tests (i.e. a layer of sand was epoxied to the bottom of the strong box container). A slip and separation interface between the buffer and the soil was specified. This
interface allowed the soil and buffer to separate with no tensile stress. An interface friction angle of $15^\circ$ was assumed for the rough geofoam-sand interface based on recommendations by Xenaki and Athanasopoulos (2001) and Kramer (1996). The normal and shear stiffness values of the interface were set to ten times the equivalent stiffness of the soil, as recommended in the FLAC manual (Itasca 2005). For the FLAC slip and separation interface, the elastic properties of the interface have no physical meaning, however they must be selected carefully to ensure numerical stability (i.e. neither too large nor too small compared with the adjacent materials).

The plane strain models were constructed in one step. Next, gravity was turned on in one step and the model was allowed to come to equilibrium. A constant amplitude sinusoidal base excitation record of 0.1g and a frequency of 9 Hz was then applied for 5 seconds to simulate the gentle shaking (vibro-compaction) that was used in the physical tests to compact the sand backfill. Following compaction, the system was brought to equilibrium once again. The base and the two vertical boundaries of the models were then excited using the same base input acceleration record used in the physical tests (see Zarnani et al. 2005) but terminated at 0.7g. The horizontal input acceleration was actually applied using an equivalent velocity record (i.e. integrated acceleration record) with base line correction to ensure zero displacement at the base at the end of shaking. Simulation runs took about 10 hours on a personal computer with a P4-3.6GHz CPU and 1GB of RAM memory. Data was acquired at a rate of 500 Hz to avoid aliasing effects and to capture the peak values of dynamic wall response induced by base shaking.

### Table 1 - Soil properties (from El-Emam and Bathurst 2004, 2005)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk unit weight</td>
<td>15.7 kN/m$^3$</td>
</tr>
<tr>
<td></td>
<td>From direct shear box tests*</td>
</tr>
<tr>
<td>Peak angle of friction</td>
<td>$51^\circ$</td>
</tr>
<tr>
<td>Residual friction angle</td>
<td>$46^\circ$</td>
</tr>
<tr>
<td>Cohesion</td>
<td>0</td>
</tr>
<tr>
<td>Dilation angle</td>
<td>$15^\circ$</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>-</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>7 MPa</td>
</tr>
<tr>
<td></td>
<td>Back-calculated from plane strain direct shear box test simulations using FLAC</td>
</tr>
<tr>
<td></td>
<td>58$^\circ$</td>
</tr>
<tr>
<td></td>
<td>46$^\circ$</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>15$^\circ$</td>
</tr>
<tr>
<td></td>
<td>7 MPa</td>
</tr>
<tr>
<td></td>
<td>6 MPa</td>
</tr>
</tbody>
</table>

* specimens 10 cm by 10 cm in plan area

### Table 2 - EPS geofoam properties (from Horvath 1995)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS density</td>
<td></td>
</tr>
<tr>
<td>12 kg/m$^3$</td>
<td>0.286 MPa</td>
</tr>
<tr>
<td>16 kg/m$^3$</td>
<td>0.5 MPa</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>12 MPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>16.8 kPa</td>
</tr>
<tr>
<td>Cohesion</td>
<td>30.5 kPa</td>
</tr>
</tbody>
</table>
NUMERICAL RESULTS

Due to page constraints, buffer deformation and soil acceleration predictions are not reported here. However, the most important measurement to quantify wall performance with and without a geofoam buffer inclusion are the histories of wall force at peak acceleration events during dynamic loading. Figures 2a through 2d provide a summary of wall force versus peak base acceleration for both physical and numerical experiments. The horizontal axes in the figures refer to the peak horizontal base acceleration acting towards the wall during the test. The vertical axis is the total horizontal earth force on a per-meter running length of wall basis.

The data for the physical tests show that there was an overall trend of increasing wall force with base acceleration in each test and this trend was captured by the numerical results. The experimental and numerical results also show that there is a significant reduction in wall force during base shaking for the two walls constructed with an EPS geofoam inclusion compared to the reference control wall without a compressible layer. Furthermore, there are small but detectable lower forces recorded for the wall constructed with the lowest EPS density compared to the wall with higher density geofoam. A summary of the numerical responses is presented in Figure 2d to highlight the performance differences between the three test configurations.

There are differences in quantitative values between numerical and physical test results at some acceleration values. For example, the force-base acceleration slope for the control wall was steeper than that for the physical experiment. However, for the geofoam buffer simulations there was good agreement over a wide range of base acceleration values. A persistent discrepancy between physical and numerical results can be noted at the end of construction following vibro-compaction. Numerical results are consistently lower at the start of the tests and during the initial application of the base excitation record. The under-prediction is in the range of 15 to 43%. This discrepancy is believed to be due to the inadequacy of the simple soil model and numerical compaction procedure adopted to generate the initial soil state in the physical experiments. In the physical tests, the soil was vibro-compacted in 200 mm lifts and this likely resulted in locked in stresses that were not generated in the numerical simulations. However, once the base excitation record applied during the physical experiments reached about 0.1g (the peak acceleration amplitude used during vibro-compaction) these locked in stresses were released. The improvement in numerical predictions can be seen to occur once this threshold peak acceleration level is exceeded.

The results of physical experiments and numerical simulations at peak base acceleration values applied at the end of numerical simulations are summarized in Table 3. The data shows that at a common base acceleration value, the reduction in total earth forces ranged from 15 to 16% in the physical tests and this range was reasonably close to the predicted range of 18 to 21% from the numerical simulations.

CONCLUSIONS

A series of numerical simulations are reported using a FLAC model to predict the dynamic load response of reduced-scale rigid walls constructed with a geofoam seismic buffer and excited using a large shaking table. The constitutive models used for the component materials in the
simulations (i.e. soil and EPS geofoam) were kept purposely simple as a first attempt to simulate the physical test results. While the earth forces at the end of construction (after vibro-compaction) were under-predicted, the predicted earth force response of the models to subsequent base shaking are judged to be reasonably accurate. The relative improvement of the geofoam models with respect to the (control) rigid wall without seismic protection was very close between physical and numerical results.

The FLAC model described here holds promise as a tool to investigate the prototype-scale response of geofoam seismic buffers using a wider range of geofoam products, compressible layer thickness, wall heights, seismic records and different soil backfills. The ultimate objective

Figure 2 – Wall force versus peak base acceleration from physical and numerical experiments

a) no geofoam inclusion (control wall)  

b) geofoam density = 12 kg/m³  

c) geofoam density = 16 kg/m³  

d) comparison of numerical results
of parametric analyses using this FLAC code (or improvements) is the development of design charts that can be used by engineers to optimize the selection of geofoam type and thickness with respect to project-specific conditions.

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REFERENCES


