Modeling A Full Scale Landslide Test

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ABSTRACT

The power of the finite element analysis method is clearly demonstrated in this case study. Finite element analysis was used to evaluate the Platepile method for stabilizing shallow landslides. The Platepile Method consists of the installation of arrays of steel elements driven vertically into the slope at spacing of 1 meter (4 feet) horizontally and 1 to 3 meters (4 to 10 feet) up and down the slope. A field testing program included full scale landslide tests. Finite element modeling predicted the maximum layer that could be stabilized by 2 meters (6 feet) long. A second full scale field test was performed to validate the effectiveness of the method for the maximum predicted layer thickness. The following discussion describes the Platepile method, the program for testing the validity of the concept and the use of finite element modeling to develop numerous varying configurations of slope conditions and soil parameters.

THE PLATEPILE CONCEPT

Platepiles consist of a steel plate welded to a steel angle. The plate captures the sliding force and the angle transfers the sliding force into the higher strength soil below the slide plane. The dimensions of the Platepiles in this study measured as follows: plate: 305 millimeters (12 inches) wide by 610 millimeters (24 inches long); angle: 64 millimeters by 64 millimeters by 6 millimeters (2½ inches by 2½ inches by ¼ inch) thick by 2 meters (6 feet) in length. Platepiles are shown in Figure 1.

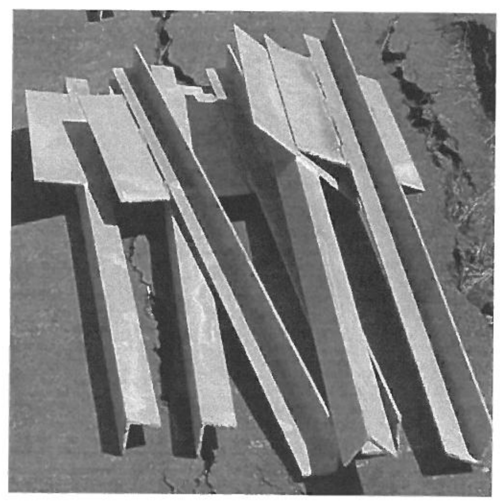

Figure 1 – Six Foot Platepiles

The concept uses the steel Platepiles to support small volumes of the potentially unstable layer. The reinforcing Platepiles are spaced side-by-side at a distance of four feet where arching of the soil prevents soil migration between the plates. Subsequent rows transverse to the horizontal are staggered and spaced dependent on the slope steepness and soil strength varying from 1 to 3 meters (4 to 10 feet). The Platepile concept is shown in Figure 2.

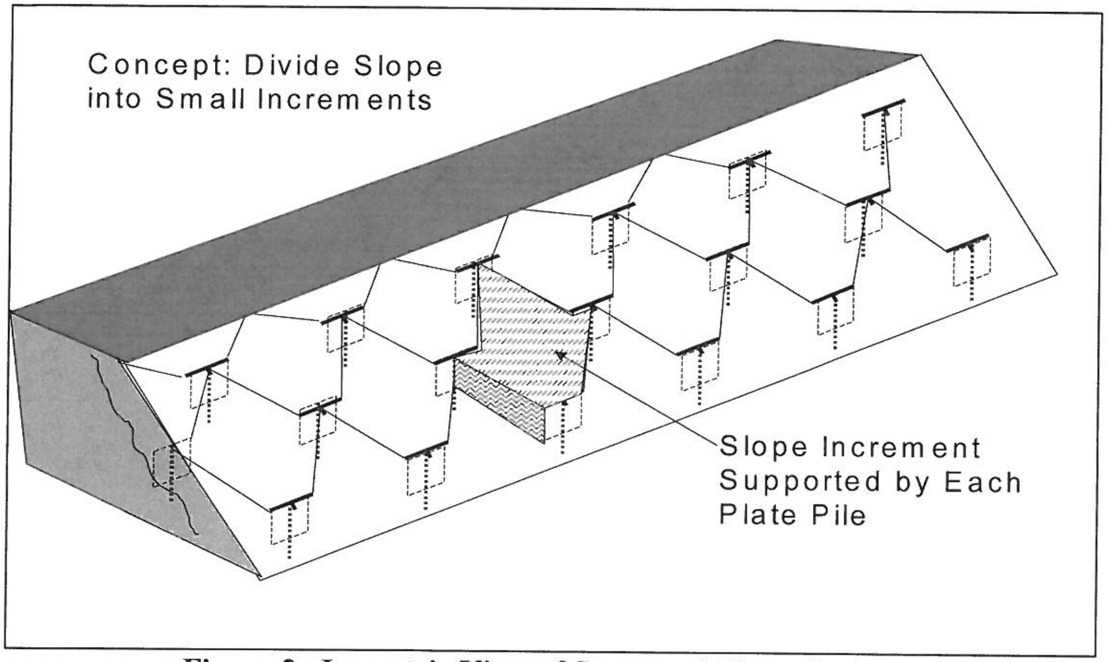

Figure 2 –Isometric View of Staggered Platepile Array

Research Analysis Program

The research analysis program was designed to test a typical Platepile layout in a full scale slide and then model the test results in a finite element analysis using the known variables from the test. The program included the following elements:

- Determine the initial element spacing required for a factor of safety of 1.5 for a 1 meter (3.3 foot) thick layer on a 2.0 horizontal to 1.0 vertical slope.
- Construct a test fill and perform full scale landslide tests with and without Platepiles.
- Model the landslide tests using the actual soil parameters and slope configuration.
- Vary the layer thickness in the model to predict the maximum effective thickness of the method.
- Perform another full scale landslide test at the predicted maximum layer thickness to validate the modeling prediction.
- Have each step of the program peer reviewed.

Initial Simplified Slope Stability Analysis

Simplified slope stability analyses were performed using conventional limiting equilibrium techniques to determine the appropriate spacing of the Platepiles in the test slope corresponding to an initial unreinforced factor of safety of 1.0. Both the infinite slope and the two dimensional method of slices analyses were performed.

Infinite slope analyses for a 1 meter (3.3 foot) thick dry soil layer with the residual shear strength parameters outlined in Table 1 resulted in a factor of safety of 1.2. Residual strength parameters were utilized since it is known that these slopes undergo some strength degradation leading to failure. In a completely saturated state, the factor of safety is reduced to much less than 1.0, indicating probably failure. Thus, it was anticipated that failure of the 1 meter (3 foot) thick unreinforced layer on the 2 to 1 slope would likely occur at some point prior to saturation after significant wetting.

The infinite slope analysis was also performed taking into consideration the strength of the Platepiles. From previous testing, it was known that the piles fail in bending at their hinge point in the steel angle section when subjected to the uniform ultimate load against the plate. A yield capacity analysis on the 64 millimeters by 64 millimeters by 6 millimeters (2½"×2½"× ¼") steel section shows that an equivalent load of 318 kilograms (700 pounds) will cause failure of the section. For a section of slope with this additional resistance, the factor of safety increases by 20%. However, in addition to the 318 kilograms (700 pounds) of resistance, the passive resistance behind the pile also adds to the resistance. Based on field tests, the combined steel bending resistance and passive resistance is in the range of 3636 kilograms (8,000 pounds).

Two-dimensional slope stability analyses were performed using the software program SLIDE in a similar manner as for the infinite slope analyses to verify these results. Analyses with plate piles were performed by using the micro-pile support module within SLIDE and showed a similar increase in the factor of safety, from a minimum of 20% for the lower end of pile resistance to upwards of 50% for higher likely values of resistance. The analyses thus validated the planned Platepile spacing and configuration of the test slope.

Test Program

The full scale field tests of the Platepile method included the unreinforced control slope and the reinforced slope recreated and subject to identical conditions, but with two rows of Platepiles spaced 1.2 meters (4 feet)

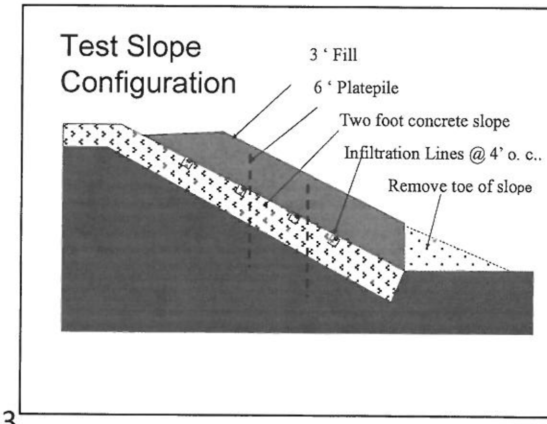

Figure 3 – Test Slope

cross slope and 3 meters (10 feet) down slope installed preceding irrigation.

Test Slope Data

Soil from a single stockpile was used and compacted at nearly identical standards. The soil used in the test represents a typical colluvial soil in the San Francisco Bay area and was obtained from a recent landslide repair. The soil was a grayish-brown highly plastic silty clay. The soil was placed and compacted by track rolling in three 305 millimeters (12 inch) lifts, with a Caterpillar D6-equivalent bulldozer. Sand cone density tests were performed to determine the relative compaction of the test fills. Test 1 fill was compacted to an average of 80.4 percent relative compaction.

Following compaction, irrigation was applied by hand sprinkling for a period of one hour using two spraying nozzles. A total of 2366 liters (625 gallons) of water were applied in each case which translated into roughly a 9 centimeter (3.5-inch) rainfall event as measured by rain gauges installed on the slope. The slopes were then allowed to dry for a 48-hour period under 32°C (90°F) + heat and direct sun. Surface irrigation was then applied again, this time for a total of 3634 liters (960 gallons) and a simulated rainfall event of between 14 and 19 centimeters (5.5 and 7.5 inches). In Test 2, an additional 189 gallons of water were added to account for higher air temperature and drying conditions on this test date. Subsurface infiltration was then initiated immediately following the end of surface irrigation using the embedded irrigation lines. In each test, bottom irrigation was turned on for 2 minutes, then turned off for 2 minutes to allow initial wetting of the system. During this time period, 379 liters (100 gallons) of water were injected. The bottom irrigation was then turned on again, this time for a 5 minute period and for a total of approximately 1514 liters (400 gallons) injected. Failure occurred at this point in Test 1 and led to a mobilized debris flow mass. No soil mobilization occurred in Test 2 (with plate piles). An additional 5 minutes of subsurface irrigation totaling 833 liters (220 gallons) was applied in Test 2 with still no failure occurring. The soil properties for the two tests are shown below in Table 1.

Table 1. Slide Zone Fill Parameters for Tests 1 and 2

Test Data	**Test 1**	**Test 2**
Reinforcement	*No Platepiles*	*With Platepiles*
Fill Relative Compaction, %	80.4	80.2
Plasticity Index, %	42	42
Initial Wetting, liters (gal.)	2366 (625)	2366 (625)
Drying time, days	2	2
2^{nd} Wetting, liters (gal.)	3634 (960)	3823 (1010)*
Water Injection, liters (gal.)	1552 (410)	1438 (380)
Water Injection, liters (gal.)	27 (7)	49 (13)
Ave. M.C. @ failure or end of test	29.9	27.7
Results	**Slope Failure**	**No Slope Failure**

*1.89 liters (50 Gallons) added to compensate for evaporation.

RESULTS

(a) (b)

Figure 4 – Test 1 without platepiles (a) during irrigation and (b) after failure.

(a) (b)

Figure 5 – Test 2 with Platepiles (a) during wetting and (b) after subsurface injection

Modeling the Landslide Tests

Initially numerous two-dimensional FLAC models were created to calibrate the model to the test slope and many of the material parameters. Although these results provided valuable insight about the behavior of the plate-pile system, the model was unable to adequately capture the effect of the "Plate" and its stabilizing effect. Each plate in the test slope engages a relatively large volume of soil mass as they "hold" the slope in place. The mass of soil exerts pressure over the plates and the pressure is transmitted to the piles which transmit pressure (roughly) into a concentrated shear force just below the interface of the soil and concrete.

By using a 3-D model to capture and quantify the pressure on the plates and the "out of plane" soil strains (compared to the 2D FLAC model) the stabilizing influence of the plate-pile system was able to be captured. Three-dimensional modeling approach was used to model the out of plane soil pressures acting on the plate-pile system. The same approach that was used in the 2D model for calibration was also used in the 3-D model using the field test slope parameters. Once the 3-D model was calibrated with the test slope, plate-pile performance under different conditions could be predicted.

A 3-D Numerical model was setup to represent the test site slope. The soil fill material was represented using a strain softening material model. Elastic material model was used for the concrete layer in the initial analysis however the model was setup with such that soil or rock materials types can be incorporated into the model in-lieu of the concrete layer in subsequent models. Elements were used at the interface of the soil and concrete planar surface to allow for relative "slip" between the two materials as most likely occurred in the field cases. The material parameters used in the 2-D analysis were used initially and adjusted in the calibration stage if necessary. This was necessary to account for differences in the 2- and 3-D Modeling approaches. The slope width (y-axis) of the model was extended four feet beyond the vertical edges of the concrete slab.

The boundary conditions and infiltration points were created in the 2D model and the fill was saturated. The model indicated 1.27 meters of movement and then could not continue because of the grid deterioration. Subsequently two Platepiles were placed in the model duplicating Test 2. The analysis predicted 0.027 meters (1 inch) displacement at the toe.

The 3D FLAC model was set up and the analyses were repeated. This time the 3D model predicted 1.5 millimeters (0.005 feet) movement with the Platepiles installed confirming the 2D analysis. To determine the limits of the Platepile effectiveness, the layer thickness was increased up to 1.8 meters (6 feet) where the upper limit was achieved. The analysis indicated that a six foot thick soil layer could be held in place on a 2 to 1 slope after saturation along the slide plane.

TEST NO. 3 - Six-Foot-Thick Slide Layer

In order to validate the model prediction, a test was designed for a 1.8 meter (6 foot) thick layer on a 2 to 1 slope. The full-scale test was designed to have the fill material as the foundation material with 10 mil sheet plastic forming the slide plane. The irrigation system was installed on top of the sheet plastic in grooves cut in the underlying fill. The test configuration is shown in Figure 6 and the test parameters are shown in Figure 7.

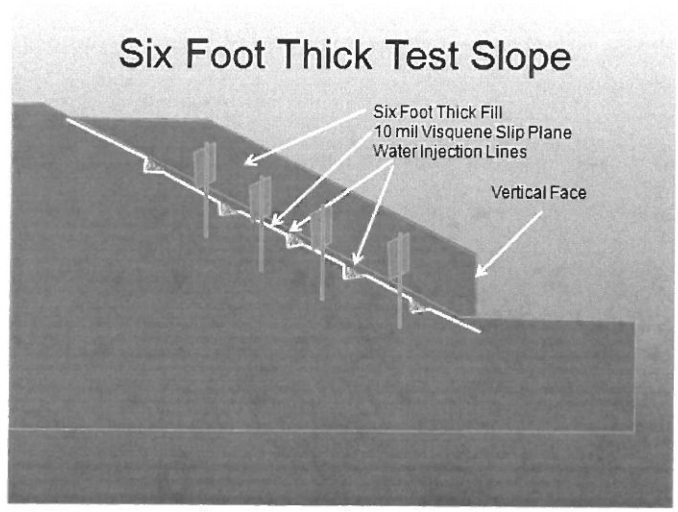

Figure 6 – 1.8 Meter (6 foot) Thick Slide Test

•	Fill Layer Thickness = 1 meter (6.0 ft.)
•	Slope = 26 degrees
•	Plate Height = 0.61 meters (2.0 feet)
•	Slope Length = 9.14 meters (30 feet)
•	Platepile Spacing = 1 meter (4 feet) (cross slope)
•	Platepile Spacing = 1-3 meters (4 – 10) feet (along slope)
•	Interface Slip Plane = 10 ml plastic

Figure 7 - Test Parameters

The test results confirmed the predicted results of less than 25. millimeters (1.0 inch) movement of the layer above the slip plane after saturation with 15,142 liters (4,000 gallons) of water injected.

Extrapolating the Test Results

After the confirmation that six feet was the upper limit of layer thickness, a series of analyses were made using various combinations of thickness, slope angle, and soil strength. The analysis results produced 160 curves for the various configurations. An example of one series of curves for a 2.0 to 1.0 slope is shown in Figure 8.

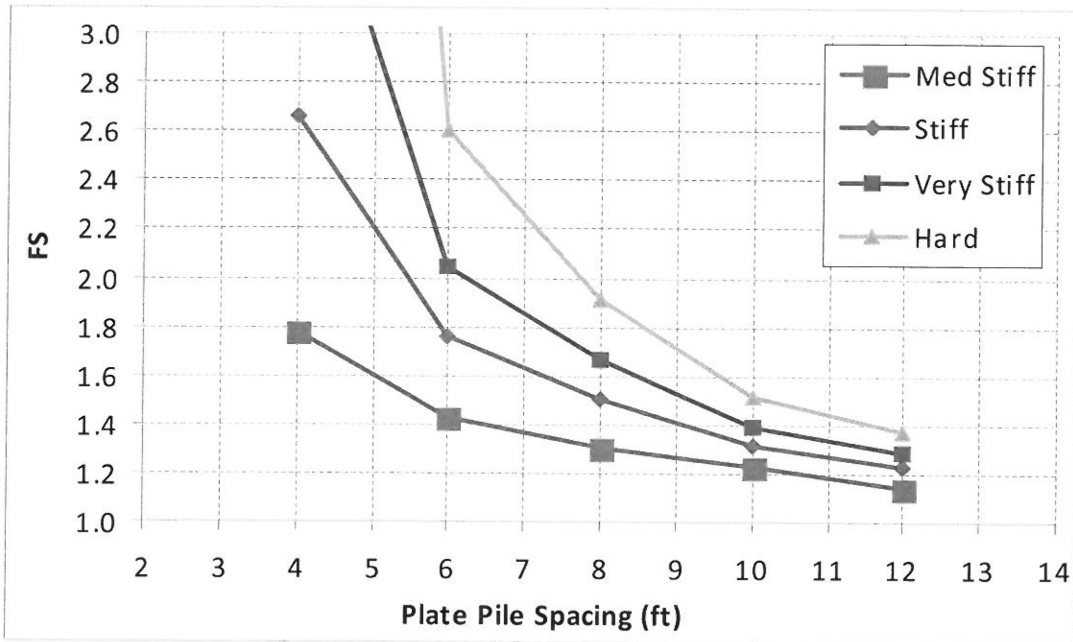

Figure 8 - Design Curves for a 2.0:1.0 Slope

CONCLUSION

The FLAC analysis was used successfully to enable the extrapolation of a single test into 160 variations of slope configuration and soil properties. A high degree of confidence in the program results were developed by conducting a second full scale test at the upper limits of the predicted effectiveness of the method.