Cost effective stabilization of clay slopes and failures using plate piles

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Abstract: Progressive, seasonal soil slips occurring on expansive clay slopes at a large, developed, landscaped commercial site, and in a slide-prone residential subdivision in Northern California, prompted a progressive shift from conventional slope reconstruction methods to a more innovative approach to slope stabilization. These sites have been plagued with predominantly translational soil slips on the order of 0.3m to 1m deep, that generally initiate after prolonged rainfall events, especially those in excess of 50mm/day. Based loosely on limited experimentation by researchers on similar shallow clay slips, Kleinfelder personnel expanded on their idea of installing 88.9mm-square plastic pins to designing 6.35mm (1/4 inch) thick galvanized steel, 63.5mm by 63.5mm (2.5-inch) angle iron with a 0.3m (12-inch) by 0.6m (24-inch) flange plate pile, approximately 2.1m long. Kleinfelder's (patent pending) technique utilizes plate piles laid out in a 1.2m-centred offset grid pattern. This stabilization method is being used to provide stabilization on un-failed and some existing failed slopes. Preliminary costs are on the order of $5 (U.S.) per square foot (9.290×10^{-2} m) of slope face, which is six to ten times less than the cost of conventional slope repairs.

Two case studies will be presented illustrating the design, use and placement techniques of the plate pile system. The commercial site case study is characterized by over 2.4 hectares of 2H:1V cut and fill slopes comprised of highly plastic clay/claystone, up to approximately 27m high. Conventional grading techniques and compaction efforts were utilized during construction in 1996-1997 to construct the slopes. Since that time, vegetation has had little success in providing deep-rooted retention of soils and prevention of shrinkage cracks and shallow soil slippage. Since completion of grading, conventional mitigation of slips has included removal of clay soils and reconstruction with select import fill (low-expansion granular material) and geogrid reinforcement or removal and replacement with rip-rap. The residential subdivision case study predominantly includes natural slopes composed of expansive soil over expansive claystone bedrock. This study also includes experimental "test" slopes created to test the lateral load of the plate piles and various plate pile patterns.

Résumé: Les glissements de terrain progressifs et saisonniers qui apparaissent dans un grand site développé et dessiné, sur des pentes d'argile étendues, et ensuite dans une subdivision d'habitation ayant tendance aux glissements de terrain en Californie du Nord, ont provoqué un changement, des méthodes de reconstruction conventionnelles à une approche, à la stabilisation côtière plus novatrice. Ces sites ont été principalement touchés par des glissements de terrain, d'un mouvement de translation de l'ordre de 1 à 3 pieds de profondeur (30,48 à 91,44 cm) provoqués en général après une chute de pluie prolongée, plus particulièrement par une période de pluie quotidienne supérieur à 2 pouces (5,08 cm). Librement inspiré par une expérimentation limité par des chercheurs sur des glissements d'argile superficiels similaires, le personnel de Kleinfelder a développé l'idée des chercheurs d'installer des goujons de 3,5 pouces carrés, ils ont conçu une équerre d'acier galvanisé d'un quart de pouce d'épaisseur, 2,5 x 2,5 pouces avec un « flange plate pile » de 12 x 24 pouces, d'approximativement 7 pieds de longueur. La technique de Kleinfelder (brevet en cours d'homologation) utilise des « plate piles » conçus dans un motif structural quadrillé « offset » (compensé?), quatre pieds « on-center ». Cette méthode de stabilisation est employée pour fournir de la stabilisation dans des zones de pentes qui se sont affaissées ou non. Les coûts préliminaires sont de l'ordre de USD$5 par pied carré de face de pente, ce qui est six à dix fois le coût des réparations conventionnelles. Deux études de cas seront présentées, qui illustreront la conception, l'utilisation et les techniques de placement du système « plate pile ». L'étude de cas de site commercial est caractérisée par plus de 6 acres (4047 m^2 = 1 acre) de pentes « cut and fill » 2H :1V se composant d'argile/pierre d'argile (claystone) très plastiques, jusqu'à 90 pieds de hauteur. Des techniques de nivelage conventionnelles et des efforts de compactage étaient utilisés pendant la construction en 1996-1997 pour construire les pentes. Depuis ce temps-là, la végétation n'a eu que peu de succès à fournir le maintien des terres avec des racines profondes, ou pour empêcher les fissures de contraction et des glissements de terrain superficiels. Depuis l'achèvement du nivelage, l'atténuation conventionnelle des glissements a inclus l'enlèvement des terres d'argile et la reconstruction avec « select import fill » (matière granuleuse de basse expansibilité) et de renforcement « geogrid », ou l'enlèvement et remplacement des terres avec du « rip-rap » (grosses pierres ou roches dures employées pour protéger une pente ou une rive contre l'érosion). L'étude de cas de site d'habitation inclus principalement, des pentes naturelles composées de terres expansibles pardessus un soubassement de pierre d'argile expansible. Cette étude inclus également des pentes « d'essai » expérimentales, crées pour mesurer la charge latérale des « plate piles » et divers motifs structuraux de « plate piles. »

Keywords: landslides, failures, clay, slope stability, remediation, piles

INTRODUCTION

Moderate to steep slopes and embankments underlain by expansive clay soils are known to be susceptible to shallow landsliding during intense and prolonged rainfall events. Slopes or embankments can consist of both natural hillslopes composed of residual and colluvial soils over weathered claystone bedrock and manufactured hillslopes consisting of engineered fills and cuts. Failure typically occurs due to an increase in pore pressure and reduction of soil strength, with progressive wetting of the near-surface clay-rich materials. This condition is further exacerbated by moisture variations due to seasonal climatic changes, that result in cyclic shrink and swell degradation of the upper soils and the formation of shrinkage cracks several inches wide and several feet deep. Shrinkage cracks act as a conduit for surface water infiltration from rainfall as well as artificially induced water from landscape watering.

In the San Francisco Bay Area of California, shallow landslides are a common occurrence. Shallow slope failures can on occasion be life-threatening, but typically are considered a maintenance problem that disrupts landscaped areas, shallow-buried utilities, low retaining walls, pavements or cause a variety of other property damage. Conventional remediation techniques typically involve removal of problematic soils or failed sections of slopes and replacement with select compacted engineered fill, earth reinforcement (geo-grid), durable stone rip-rap armoring or construction of retaining structures. These remediation techniques are commonly cost prohibitive, disruptive to adjacent sloped areas and difficult to construct on sloping ground.

A new slope stability remediation technique has been developed over the past two years to address shallow slope instability in clay-rich soils. This technique involves direct-drive or pushing approximately 2.1m-long, steel angle piles into existing landslides and potentially unstable clay slopes. The piles are constructed of 6.35mm (¼-inch) thick galvanized steel angle iron, 63.5mm by 63.5mm, with a 0.3m by 0.6m flange plate welded to the top of the pile. The "plate piles" are installed in an offset, staggered grid pattern on 1.2m centers. This stabilization method is currently being used at two sites in Northern California. Preliminary cost estimates for stabilization at these sites are approximately $5 (U.S.) per square foot of slope face (1 sq foot = 0.0929 sq meters). These costs are six to ten times less than the costs of conventional slope mitigation.

The two case studies presented, a commercial site and a residential site with open space, will describe the design approach developed for the plate piles. These studies will also describe the geotechnical analysis and demonstrate the engineering and cost effectiveness of this new mitigation technique.

LANDSLIDE CHARACTERISATION

Shallow landslides commonly occur on moderate to steep slopes and embankments underlain by expansive clayey materials. Slopes or embankments can consist of both natural hillslopes, composed of residual and colluvial soils over weathered claystone bedrock and manufactured hillslopes, consisting of engineered fills and cuts. The expansive nature of the soils makes them susceptible to seasonal, cyclic shrink and swell with variation of moisture content. At the two sites described in this study, Plasticity Indices vary between 40% to 70%. In the San Francisco Bay Area of California, the depth of seasonal moisture fluctuation is generally considered to be greatest within the upper three feet of the ground surface. Shrinking and swelling due to climatic variations results in degradation of the upper soils and the formation of inherent zones or planes of weakness parallel to the ground surface, due to creep (the slow downhill movement of soil due to gravity). Seasonal soil shrinkage can result in the formation of shrinkage cracks several inches wide and several feet deep. Shrinkage cracks act as a conduit for surface water infiltration from rainfall as well as artificially induced water from landscape watering.

Shallow landslide failures in clays typically occur due to an increase in pore water pressure and reduction in soil strength with progressive wetting. Clayey soils tend to absorb large quantities of water during rainfall events. The increase in water pressure may cause strength loss in the unsaturated portion of the soil from a reduction of effective cohesion or a reduction of effective normal stress on the shear plane (slip surface) in the saturated portion of the soil. The study sites have typical annual rainfall of approximately 760mm±, with the majority of the rainfall occurring between November and March. Intense storms typically occur in January and February. Landslide generation predominantly occurs after prolonged periods of rainfall and especially in response to storm events of greater than 50mm per day following prolonged antecedent rains.

The landslides vary in depth from 0.3 to 1m-deep and range in width from 3m to several tens of meters wide (Figure 1). The failure surface is parallel to slope and the landslides are most closely described as translational earth block slides (after Varnes, 1978), with some flow deformation at the toe. Debris within the landslides typically consist of soft to stiff, wet clay (either residual/colluvial soils or clay fill), which is underlain by either stiff to hard claystone or claystone-derived engineered fill.

Figure 1. Translational landslide on landscaped slope

CONVENTIONAL REMEDIATION

As would be expected, conventional landslide remediation measures typically address mitigation of the failed portion of the slope and rarely considers strengthening of those portions of the slope that are beyond the limits of the failure. Various methods of landslide remediation have been summarized by Rogers (1992). Most of the conventional mitigation techniques, however, are not applicable to shallow translational failures due to economic constraints and the disproportionate volume of earthwork and aerial extent of slope disturbance. In Northern California, shallow translational landslide mitigation generally consist of the following:

- Remove and replace with recompacted engineered fill
- Remove and replace with recompacted select (low plasticity), granular fill
- Remove and replace with geogrid reinforced recompacted fill
- Remove and replace with durable stone rip-rap armouring
- Flattening of the slope gradient

The techniques used to mitigate shallow translational landslides involve removal of the failed material. This typically involves disturbance of significant areas adjacent to the failed portion of the slope in order to access the landslide site and conduct the required earthwork. This, and the use of imported select fill and geogrid reinforcement can significantly add to the costs of the remediation, especially on commercially landscaped and improved slopes. In addition, removal of the failed materials may require transportation and disposal costs. At the commercial case study site, the preferred method of slope stabilization was removal and replacement with geogrid reinforced, select import fill. The techniques used to mitigate shallow translational landslides are effective, however, they are not considered economically feasible to stabilize large areas of potentially unstable slopes. Given the economic and grading constraints, a more easily implementation, cost-effective slope stabilization method was developed.

PLATE PILE STABILIZATION TECHNIQUE

It was Plato that said, “Necessity is the mother of invention”. The two case study sites described in the following examples both had large areas of unstable and potentially unstable slopes that required an innovative and cost-effective stabilization technique that would limit the amount of ground disturbance. This was especially important for the commercial site that had high, landscaped engineered fill slopes adjacent to two major streets as well as adjacent commercial and residential properties. The landslides identified on the commercial site appeared to have occurred at random locations on the slope portions and during various rainfall scenarios. Field observations over a period of ten years noticed that the majority of the 2H:1V (horizontal to vertical) slopes appeared to at least be marginally stable and that most of the landslides occurred after very intense storms. Based on these observations, it was assumed that all the surficial soils on the slopes needed was a “boost” in their resistance to sliding.

Loehr, Fennessey & Bowders (2002) describe a method of stabilizing shallow slope failures at two sites along highways in Missouri with recycled plastic pins. That method utilized 88.9mm by 88.9mm by 2.4m long plastic reinforcing members (pins) installed on a 1m centres staggered grid. Loehr, et al. (2002) indicate that evidence to date suggests that the two test landslides have been successfully stabilized, however, they point out a number of potentially limiting factors in the use of recycled plastic pins. These potential limitations include the lack of a generally accepted design procedure, the capacity, the durability, the effects of creep and the availability of plastic reinforcing members. They also indicate that the use of plastic pins can be labour-intensive depending on actual site and access conditions. Our initial attempts at evaluating the use of recycled plastic pins in California showed that it was difficult to find a manufacturer and that setup costs were prohibitive for our commercial site.

We took the concept of “pinning” the slope to increase the soils resistance to sliding to a new dimension by utilizing steel “plate piles”. The plate pile mitigation technique (patent pending) is based on increasing the resistance to sliding through shear stress absorbing bending elements installed vertically into the slope. This concept is similar to the “pin-pile” stabilization technique occasionally used for large deep-seated landslides (Ito, Matsui & Hong, 1982; Poulos, 1995; Viggiani, 1981). In a typical application, the bending elements are 1.8m to 2m long, 63.5mm by 63.5mm galvanized (6.35mm thick) steel angle iron sections with a 0.6m by 0.3m wide, rectangular steel plate welded to one end (Figure 2). (Note: dimensions in Figure 2 are given in imperial units with conversions factors given. Lengths of 6 feet were considered in slope stability analyses. However, for ease of manufacturing and cost savings, pile lengths were designed at 6’8” so that 3 piles could be manufactured from a standard 20-foot-long angle iron section).

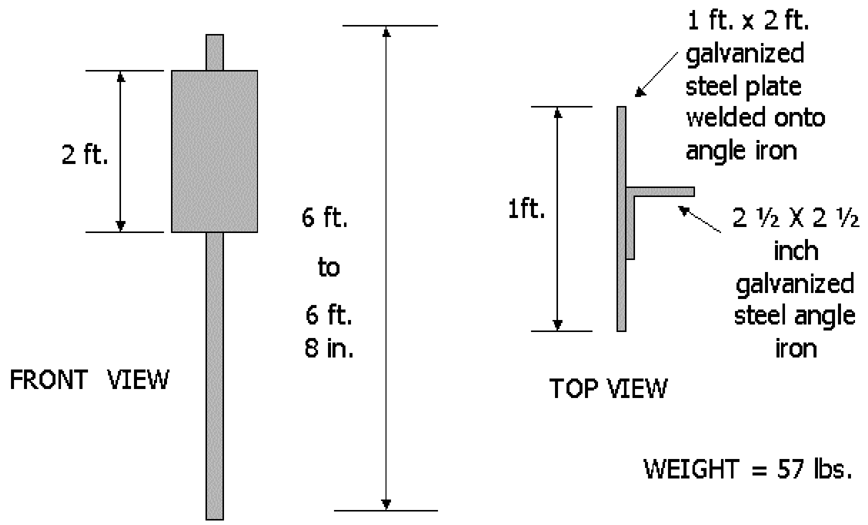

Figure 2. Plate pile design (Note metric unit conversions: 1ft. = 0.3048m, 1 in. = 25.4mm, 1 lbs = 0.4536kg)

The plate piles are pushed or driven into an existing landslide or potentially unstable slope consisting of 0.6m to 1m feet of soil or degraded clay fill over stiffer bedrock or fill (Figure 3). Since the plate piles are driven, the underlying bedrock or fill must be sufficiently weak to allow penetration without undue stress on the pile. Plate piles have been successfully driven into fill, claystone and weak sandstone. The plate reduces the driving forces of the upper slope mass, transferring the load to the stiffer subsurface strata.

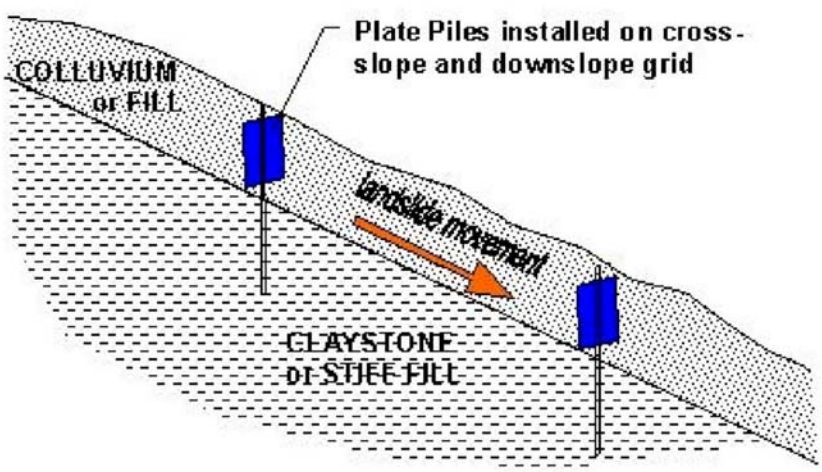

Figure 3. Schematic cross section of plate pile mitigation technique

Initially, infinite slope stability analysis was conducted at the commercial site to assess pertinent soil engineering properties and determine an appropriate pattern of reinforcement for a test section in a small landslide. Slope stability analysis was conducted for saturated slope conditions for depths of 2 and 3 feet (typical depth of landslides). Back-calculated soils parameters for an assumed static (existing unfailed slope) Factor of Safety (F.S.) of 1.0 resulted in a friction angle (Φ) of 30° and a cohesion of 2.3kPa. Based on these parameters, the passive resistance of the plate and the lateral resistance (bending moment) of the angle iron was computed to achieve a F.S.=1.5 (standard F.S. design). The preliminary analysis indicated that the critical component in determining initial pile spacing was the angle iron resistance. Plate piles in the initial test section were installed on a staggered grid pattern at 1.21m centres.

Depending on the stiffness of the underlying materials, plate pile can be installed either by direct push method by an excavator bucket or driven by either a hoe-ram or “head-shaker” compactor attached to an excavator or backhoe, equipped with a modified “cup” that fits over the end of the plate pile (Figure 4). Plate piles are sufficiently light (approximate 27kg) and can by manoeuvred and placed into position by a single labourer. Depending on site and access conditions, plate piles can be installed at rates of 20 to 25 per hour.

Figure 4. Installation of a plate pile with a modified hoe-ram attachment on an excavator

CASE STUDY-COMMERCIAL SITE

The commercial site is a 13 hectare parcel consisting of a large, relatively flat pad bordered on three sides by fill slopes up to 18 meters high and on one side by a cut slope up to 27m high. Approximately 2.4 hectares, (18% of the site) is occupied by slopes. The commercial centre was created by mass grading of a small ridge underlain by interbedded claystone and volcanic tuff deposits. Fill slopes were constructed as engineered, drained fills compacted to a minimum relative compaction of 90% (ASTM D1557). Approximately 2/3 of the fill material is composed of highly plastic, highly expansive clay. Plasticity Indices of the clayey materials at this site range from 40% to over 70%. Both cut and fill slopes were constructed at gradients of 2H:1V. Shortly after completion of grading, randomly located shallow landsliding began to occur in direct response to intense and prolonged rainfall events. Localized, shallow translational landsliding has continued to occur during the winter for the past ten years. Although these landslides have not been life-threatening, they have caused significant damage to landscaping and irrigation lines and are visually unpleasing to the community. Although global stability of the 2H:1V fill slopes has been analyzed and determined to be above a F.S of 1.5, recent infinite slope stability analysis and the time-history of shallow landslide development at this site indicated that the majority of the slopes should be considered potentially unstable

Prior to the development of plate piles, landslide mitigation consisted primarily of two schemes: remove and replace with geogrid reinforced select (low plasticity granular) import fill or remove and replace with durable stone rip-rap. Typical costs for such repairs in 2004 U.S. dollars were on the order of $30 or more per square foot of slope face. Annual costs for slope repairs were on the order of $100,000 to $300,000. Based on the data collected since construction, it was estimated that long-term mitigation costs to stabilize the remainder of the 2.4 ha of slope would total more than $5.5 million (U.S. current value) using the conventional remove and replace methods.

Plate piles installation began on this site in 2003 with a test section within a small landslide. Since 2003, 7,000 additional plate piles have been installed on the slopes in the staggered, 1.2 meter-on-centre grid pattern. To date, no movement has been detected in that test section or in any of the pile locations. An additional 3,000 plate piles are scheduled for installation before the end of 2006 to complete stabilization of the slopes. Due to localized pricing for galvanized steel, 9.5mm (3/8-inch) thick ungalvanized steel was used in lieu of 6.35mm (¼-inch) galvanized for approximately the same unit cost. The thicker steel was considered appropriate for a design life of at least 75 years. Preliminary soil corrosion tests for this site indicated that the 9.5mm (3/8-inch) steel would only experience pinhole perforations within approximately 90 years. Estimated total costs of slope stabilization using plate piles is less than $1 million (U.S.) or approximately 6 times less than the conventional remove and replace methods.

CASE STUDY-RESIDENTIAL TEST SITE

The residential test site is located within the Blackhawk gated residential development in Northern California. The slopes surrounding this development have been prone to numerous shallow landslides that have developed within residual and colluvial clayey soils, typically underlain by weak claystone bedrock. To test the effectiveness of the plate pile stability method, a series of full-scale field tests were performed at the Blackhawk Geologic Hazard Abatements District (GHAD) Test Site. Short, et al. (2005, in press) have summarized the testing and evaluation procedures that demonstrate the effectiveness of plate piles in stabilizing shallow landslides and potentially unstable slopes underlain by clay. Short, et al. (2005) experimented by constructing a 2H:1V (26.6°) test fill slope underlain by a concrete slab outfitted with irrigation lines (to simulate pore water pressure) and a geometric arrangement of PVC tubes/sleeves in which various configurations of plate piles can be inserted (Figure 5).

Figure 5. Concrete slab at test site outfitted with an array of plate pile sleeves and subsurface irrigation lines

The slab is designed to act as a predetermined slip surface or zone of weakness on which to initiate slippage. As part of the testing, a 1m thick layer of compacted clay fill was placed over the concrete slab. During the experiment, the surface was soaked (to simulate a rain event) and then the irrigation lines embedded in the subsurface concrete slab were turned on to increase the effective pore pressure acting on the base of the soil and soil/concrete interface (slip surface). The test continued in the unreinforced slope until translational failure was initiated within approximately 7 minutes. The test was then repeated, this time with plate piles inserted into the sleeves in the concrete on a 1.2m-on-center lateral spacing, in rows 3m apart. Short, et al. (2005) show that failure did not occur in the second trial, even after 13 minutes of subsurface irrigation. It should be noted that no tension cracks formed and excess water from the subsurface irrigation lines exited the slope through "piping", without loss or movement of the soil mass. The 1.2m by 3m offset grid pattern that was shown to be stable resulted in a stabilized configuration using less plate piles than that in the commercial, further reducing the cost of stabilization by an additional 50%.

Another series of tests was performed to determine the ultimate strength and yield capacity of the piles, as well as the mode of failure of the piles. Load cell tests indicate that the plate piles obtain peak load strengths on the order of 22kN to 31kN and that the mode of failure is by bending at the point of fixity. These tests also show that there is a load distribution and arching effect in the soil between the plate piles. Short, et al., (2005) show that slope stability analyses for the test slope conditions resulted in a 20% to 50% increase in the F.S. against translational sliding failure.

CONCLUSIONS

Shallow (0.3m to 1m deep) translational landsliding is a common occurrence in moderate to steep slopes underlain by clayey materials. These slopes typically fail in response to intense storms following prolonged rainfall events that act to reduce soil strength due to increasing pore water pressures. Slopes can be natural, underlain by residual and colluvial soils, or graded slopes, constructed of compacted engineered clay fill. Although commonly considered maintenance issues, shallow slope failures can cause significant and costly property damage.

Plate pile mitigation for shallow landslides has been developed to stabilize slopes with minimal slope disturbance and significant costs savings. Conventional remediation techniques typically include removal of the failed material or potentially unstable slopes and replacement with higher strength engineered fill or durable stone rip-rap. Plate piles consist of 1.8 to 2.1m long galvanized 9.5mm thick steel angle iron with a 0.3m by 0.6m plate welded at one end. Plate piles are pushed or driven into the ground in a staggered offset pattern, using a standard excavator or backhoe equipped with a modified cup attachment. Field implementation and controlled slope experiments have shown that the plate pile technique can increase the static Factor of Safety against slide 20% or greater and can reduce the cost of slope stabilization 6 to 10 times that of convention slope repairs.

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