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# STABILIZING LANDSLIDES USING RAMMED AGGREGATE PIERS

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## ABSTRACT

Very dense and stiff rammed aggregate pier elements have been used as a soil reinforcement method since 1989 beginning in the United States and propagating to Europe and Asia. Reliable performance coupled with cost and construction time saving, have made this ground improvement method an attractive alternative to gravity walls and to reinforced earth systems for landslide stabilization. This ground improvement system is unique with modulus of stiffness of the piers measured to be 10 to 45 times greater than unimproved soils. Its unusually high internal shearing resistance is highly effective as a means of stabilizing failing slopes, and providing increased factor of safety against global failures within displaced soils. This paper presents the construction processes, technical concepts as well as the feasibility of using the rammed aggregate pier system as a “dowel pile” system within the residual soil slopes.

## INTRODUCTION

Rammed aggregate pier elements have been used to support compressive loads applied by footings, floor slabs, and steel storage tanks for more than a decade [1]. The effectiveness of the piers is attributed to the lateral prestressing that occurs in the matrix soils during pier construction and to the high shear strength and stiffness of the aggregate pier itself. Applications of rammed aggregate pier elements for stabilizing landslides have been proven to be highly effective in stabilizing active landslides as well as preventing potential landslides and global instabilities. This paper presents:

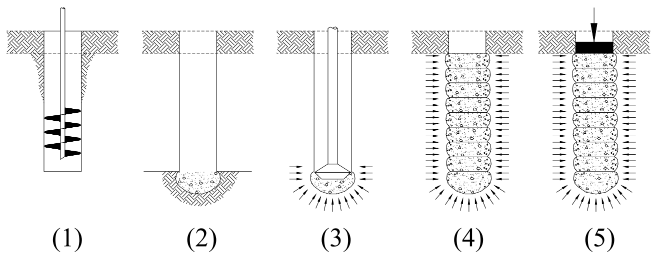
1. Results of field and laboratory tests performed to evaluate the shear strength of the rammed aggregate pier elements,
2. Design methods implemented to evaluate the effectiveness of soil stabilization with rammed aggregate pier elements, and
3. Descriptions of project conditions and design approaches used for two projects in the United States where rammed aggregate pier elements were used to stabilize landslides.

This paper is of particular significance because it provides descriptions of design methods for improving global stability, as well as field and laboratory test results associated with this rapidly growing, soil reinforcement method using the rammed aggregate piers.

## CONSTRUCTION

Construction of rammed aggregate pier elements is well described in the literature and shown in Figure 1 [2], [3], [4], [5]. The piers are installed by drilling 610 mm to 915 mm diameter holes to depths typically ranging between 2 m and 8 m below working grade elevations (Figure 1, Panel 1), placing thin lifts of aggregate stone within the cavities, and compacting the aggregate using a specially designed high-energy beveled impact tamper. The first lift consists of clean stone and is rammed into the soil to form a bottom bulb below the excavated shaft (Figure 1, Panels 2 and 3). The bottom bulb effectively extends the design length of the aggregate pier element by one pier diameter. The piers are completed by placing consecutive 0.3 m thick lifts of aggregate over the bottom bulb and densifying the aggregate with the beveled tamper (Figure 1, Panel 4). During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface. The final step is a preload application, applying a downward force on top of the completed pier for a preset period of time. This preload effectively prestresses and pre-strains the pier and adjacent matrix soils and further increases the stiffness and capacity of the system.

The elements may be installed to penetrate through weak and compressible soils thus offering improvements in the composite shear strength and the composite compression characteristics of the reinforced deposit.




(1) Drill cavity.
(2) Place stone at bottom of cavity.
(3) Ram stone to form bottom bulb.
(4) Densify stone in lifts to form undulated-shaft.
(5) Preload top of the rammed aggregate element.

**Figure 1: Construction Process**

## FIELD AND LABORATORY TESTS

Field and laboratory tests have been performed to investigate the engineering properties of the rammed aggregate piers. The high shear strength of the elements has been measured by performing full-scale direct shear tests at the tops of installed aggregate pier elements [6] and laboratory triaxial shear tests on reconstituted samples [7].

Full-scale direct shear test results, shown on Figure 2, indicate a friction angle of about 49 degrees for piers constructed from open-graded stone (no fines) and a friction angle of about 52 degrees for piers constructed from well-graded stone (5 to 10 % fines). Laboratory triaxial tests indicate a friction angle of 51 degrees for piers constructed from well-graded stone.

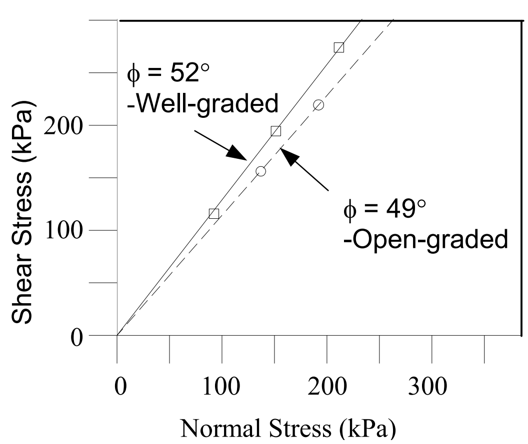



**Figure 2: Results of full-scale direct shear tests**

## ANALYSIS METHODS

Analysis methods used in utilizing the rammed aggregate pier system to increase global stability and stabilize landslides are based on classical geotechnical engineering approaches combined with the shear strength characteristics of the aggregate pier elements [8].

### Shear reinforcement

The unusually high internal shearing resistance of the rammed aggregate pier elements contributes to soil reinforcement and to stabilizing failing slopes. Rammed aggregate piers reinforcing elements are installed to intersect potential critical shearing surfaces thereby increasing the factor of safety against global instability (Figure 3). Analyses of the factor of safety against instability are performed using conventional geotechnical slope stability computer programs [9].

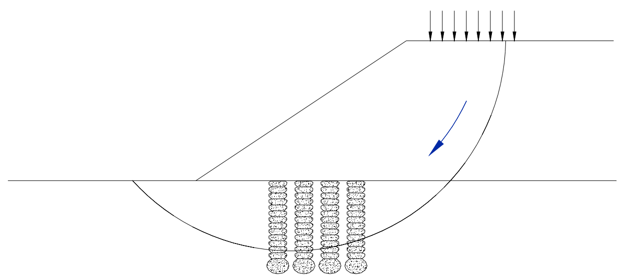


**Figure 3: Global stabilization using rammed aggregate pier elements**

The composite shearing strength parameter values of the composite soils reinforced by the rammed aggregate pier elements are computed using the conventional method of simply calculating the weighted average of the shear strength components of the aggregate piers and matrix soil materials [10]. The composite cohesion intercept ($c_{comp}$) is computed with the expression:

$$c_{comp} = c_g R_a + c_m (1-R_a) \ , \qquad (1)$$

where $c_g$ is the cohesion intercept of the pier aggregate, $c_m$ is the cohesion intercept of the matrix soils, and $R_a$ is the ratio of the sum of the total pier element cross-sectional area to the gross footprint area of the reinforced soil zone. The cohesion intercept of the aggregate is zero. The composite friction angle ($\phi_{comp}$) is computed with the expression:

$$\phi_{comp} = \arctan [R_a \tan \phi_g + (1-R_a) \tan \phi_m] \ , \qquad (2)$$

where $\phi_g$ is the friction angle of the pier aggregate and $\phi_m$ is the friction angle of the matrix soils.

## CASE HISTORIES

### A North Carolina Landslide, USA

The combination of heavy rains and an excessively steep fill slope resulted in a landslide at a commercial development in Raleigh, North Carolina, USA during the winter of 1997-1998. A parking lot and loading dock for a large commercial superstore were located at the top of the 20-m tall fill slope. A heavily traveled roadway is located adjacent to the toe of the slope.

The slope consisted of compacted residual silty sand and sandy silt fill derived from parent Piedmont physiographic soils. The residual soils typically have long-term effective friction angles on the order of 28 to 30 degrees. The compacted soil slopes were built at slope ranging from 2 horizontal to 1 vertical (2H:1V), to as steep as 1.5H:1V. The steep slope inclinations, combined with heavy seasonal rainfall, contributed to a series of shallow compound landslides. The resulting slides encroached on the parking area at the crest and the adjacent property and roadway at the toe.

The initial repair scheme consisted of excavating a trench below the slide mass and backfilling with a gabion wall toe buttress. The planned depth of the excavation required staged construction and shoring, as well as the removal of a significant amount of soil. Significant drawbacks to such a repair solution included excessive costs as well as a long construction schedule.

In lieu of the planned excavation, rammed aggregate pier elements were installed to support the gabion wall (Figure 4). The 3-m long piers extended through the critical failure surface of the slope. Attributing to the very high friction angle of the rammed aggregate (on the order of 50 degrees) installation of aggregate piers within weak matrix soils increases the composite shearing resistance of the reinforced zone. Also, lateral compaction during construction provides increases in both shear strength and stiffness modulus of the matrix soil between the rammed aggregate pier elements. Figures 5 and 6 illustrate the pier construction at the site and the final constructed slope, respectively. As a result of rammed aggregate pier installations, construction risks and costs associated with the slope repair were reduced and the construction schedule was accelerated in comparison with alternative repair options.

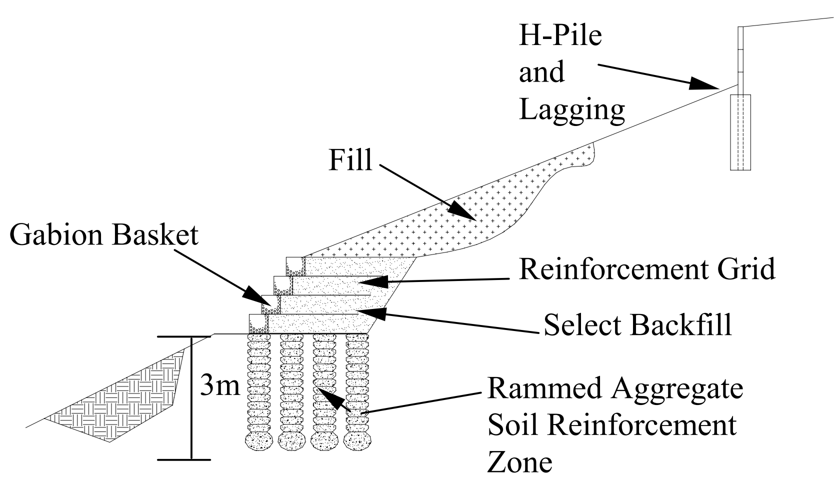



Figure 4: Slope stabilization using rammed aggregate piers

Figure 5: North Carolina landslide repair: during construction


Figure 6: North Carolina landslide repair: after construction

**Landslide Repair, Dallas County, Iowa, USA**

For years, Dallas County (Iowa) roadway engineers have been troubled by a problematic landslide along state route P48. Development of the slide is associated with the construction of the road itself. A significant amount of surcharging occurred at the top of the future slide as a result of the roadway grading operations during construction. Geotechnical engineers working on the problem believe that the grade changes affected the natural groundwater flow down the slope. The additional loading, coupled with a zone of weak shale and groundwater flow within the slope, resulted in a constant problem of lateral roadway displacements. The displacements have been so severe that paving of the road has never been undertaken.

The geotechnical conditions at the site consist of clay embankment fill soil underlain by Wisconsonian and Pre-Illinonian glacial till comprised of sandy lean to fat clay. The glacial till soils are located immediately beneath the constructed embankment. The till is underlain by weak shale at depths on the order of 6.0 to 7.5 meters below existing grade. The shale layer exhibits a friction angle on the order of 8 to 10 degrees. The low friction angle of the shale layer resulted in movements of the overlying soil along the shale/soil interface and is the cause of the landslide movements along route P48.

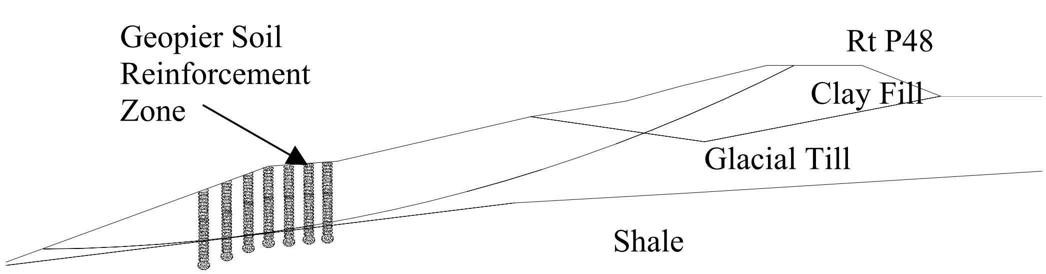



Figure 7 Landslide repair, Dallas County, Iowa, USA

Figure 8 Construction for landslide repair, Dallas County

In order to prevent further movement of the slide, it was essential to increase the shearing resistance of the weak shale layer. A total of 579 rammed aggregate pier elements were installed to depths of up to 9 meters (Figures 7 and 8). The piers were installed into the weak shale layer to strengthen the weak interface between the shale and the overlying soil. To minimize problems with groundwater infiltration within the pervious piers, a 1.5-m clay cap was constructed in the upper portion of each pier. The rammed aggregate pier soil reinforcement solution resulted in a cost of US$170,000. This represented a cost savings of US$700,000 relative to the other considered solutions.

**Case Histories Summary**

Table 1 summarizes the above two unstable slope reinforcement projects involving massive landslides that were successfully and economically corrected by rammed aggregate piers soil reinforcement:

**Table 1: Summary of landslide reinforcement applications**

| Project | Matrix soil friction angle prior to rammed aggregate piers reinforcement | Composite friction angle after rammed aggregate piers reinforcement | Safety factor after rammed aggregate pier stabilization |
|---|---|---|---|
| Lynn Road landslide, Raleigh, NC, USA | 28 degrees | 38 degrees | 1.35 |
| County Road P48, Dallas County, IA, USA | 6 degrees | 15 degrees | 1.12 |

**CONCLUSIONS**

This paper discusses the construction process of the rammed aggregate pier system and design methods using this soil reinforcing elements for stabilizing landslide and improving global stability. The high shear strength, with an internal friction angle ranging from 49 to 52 degrees, exhibited by the aggregate pier elements, allows for substantial increases in the composite shearing resistance within slopes, thereby providing higher global factors of safety against instability. Case histories are presented where the rammed aggregate pier elements have been successfully used to provide economical solutions for difficult landslide stabilization problems.

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