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Centrifuge modelling to study the effect of root spacing on load transfer mechanism in vegetated slope

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Abstract

Failure of slopes has been a frequently occurring hazard, which leads to loss of life and resources. To stabilize the slopes, vegetation has been used, where stump of plant roots act as passive piles by providing mechanical reinforcement. In this research, effect of spacing of trees on load transfer mechanism in a slope has been studied and comparability of passive piles and roots has been investigated. Half portion of an embankment has been taken and simplified instrumented roots were planted in staggered pattern on the slope. Two models with spacing of 3 times the diameter of root and 6 times the diameter of the root were prepared to study the effect of spacing on load transfer mechanism. A model with no reinforcement (fallow) has also been tested. During the test, load was introduced to a foundation at the crest of slope till the slope failed. It was observed that as the spacing increases, load bearing capacity of slopes decreases. As spacing of roots decreases, incidence of failure prolongs. Also, as the spacing of roots decreases, shear failure plane gets deeper in the slope. As these aspects of passive piles were observed, behaviour of roots is comparable to that of passive piles.

Keywords: Soil arching, spacing of roots, reinforcement, slope stabilization, shear failure plane.

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1. Introduction

Slope failure, both man-made and natural is one of the frequently occurring hazard. To avoid loss of life and resources, various reinforcement techniques have been used to stabilize slopes. Stabilization can be done by both man-made and natural resources. Stabilization by using vegetation has been proposed and various research has been conducted on the reinforcement characteristics of grasses and trees. Trees provide reinforcement primarily using its roots. Root consists of two parts, the upper part of root hair provide hydro-mechanical reinforcement by absorbing water in the soil, which can be beneficial to slope stability (Duckett, 2013). Second part is root stump, which constitutes of majority of area of the root system and provides mechanical reinforcement.

According to a study (Mickovski, Bransby, Bengough, Davies & Hallett, 2010), root stumps act in a comparable manner to soil reinforcing additions such as passive piles, anchor etc. The phenomenon using which passive piles stabilise the slopes is known as soil arching. As displacement of soil occurs in the slope, soil is forced to go through the space between piles, provided that piles act as non-yielding support. Thus, shear stresses are developed due to the relative movement of soil with respect to piles at the interface. “This development of shear stress and transfer of load from a yielding support (displacing soil) to an adjacent non-yielding support (piles fixed in non-yielding soil strata) is known as soil arching” (Bosscher, Grey & members, 1986).

Previous studies involving roots were done to study the reinforcement characteristics of roots on slope. But the mechanism behind the reinforcement has been an area of debate as to whether it is comparable to passive piles. Also, investigations done so far had used real plant roots to study the reinforcement effect of root e.g. Askarinejad & Springman 2015 and Mickovski et al. (2011). Major limitation of this is the inability to control the growth of roots and repeatability of tests. To overcome this drawback, Sonnenberg et al. (2012) used linden wood sticks and Viton O-ring rubber to reproduce the effect of stiff and flexible roots respectively. But drawback of this technique is that the mechanical properties of materials used were not exactly the same as those of roots. Thus, 3D printed roots with properties similar to roots of trees were used in the study done by Liang (2015).

Laboratory tests done to study the effect of reinforcement of roots and pull out resistance in soil has been done using direct shear tests (Duckett, 2013; Eab, Likitlersuang & Takahashi, 2015). Root reinforcement models were made using these test results along with properties of roots. Limitation of such test is that shear failure plane is imposed to the soil. Thus, real scenario of failure cannot be replicated (Duckett, 2013; Liang et al. 2017). Physical modelling using geotechnical centrifuge can be done to overcome this drawback as slopes can fail in their natural way and data comparable to prototype can be obtained. Also, trap door tests and other 1g laboratory and full-scale tests have been done to study the effect of spacing on load transfer mechanism only using a single row of roots (Bosscher et al. 1986; Kahyaoğlu, Onal, Imanch, Ozden & Kayalar, 2012). In reality, based on the size of the slope, more than one row of roots can be used for better reinforcement and no experimental study has been done on the same.

This research investigates the effect of spacing of roots on load transfer mechanism between roots and soil using centrifuge modelling. Phenomenon of soil arching is studied by reinforcing the slope using simplified taproot stump at predetermined spacing. Behaviour of root stumps when the slope fails is recorded by instrumenting the roots and the load displacement curve for each model is obtained. Moreover, the staggered group effect of roots in slopes has also been studied. Shear failure plane of each model slope is obtained using advanced image analysis and is used to explain the response of model.

2. Experimentation

Figure 1 shows the slope plan for all the tests done in this study. In the model scale, the slope length was 134.5 mm. The inclination of slope was 33° and steeper slope could not be made as dry sand used in the test had an angle of repose of 33°. Tests were done at 30*g* using the Geo-centrifuge at Delft University of Technology which is a beam type centrifuge with two swinging carriers and maximum payload of 500 N at 300*g*. Scale factor of 30g was chosen in order to model the largest slope possible while maintaining the size of the printed roots below the optimum size of real roots. Dimensions and values obtained for model scale in centrifuge can be extrapolated to prototype scale using scaling laws which is given in Table 1. This contributes to a slope of length 4 m in prototype.

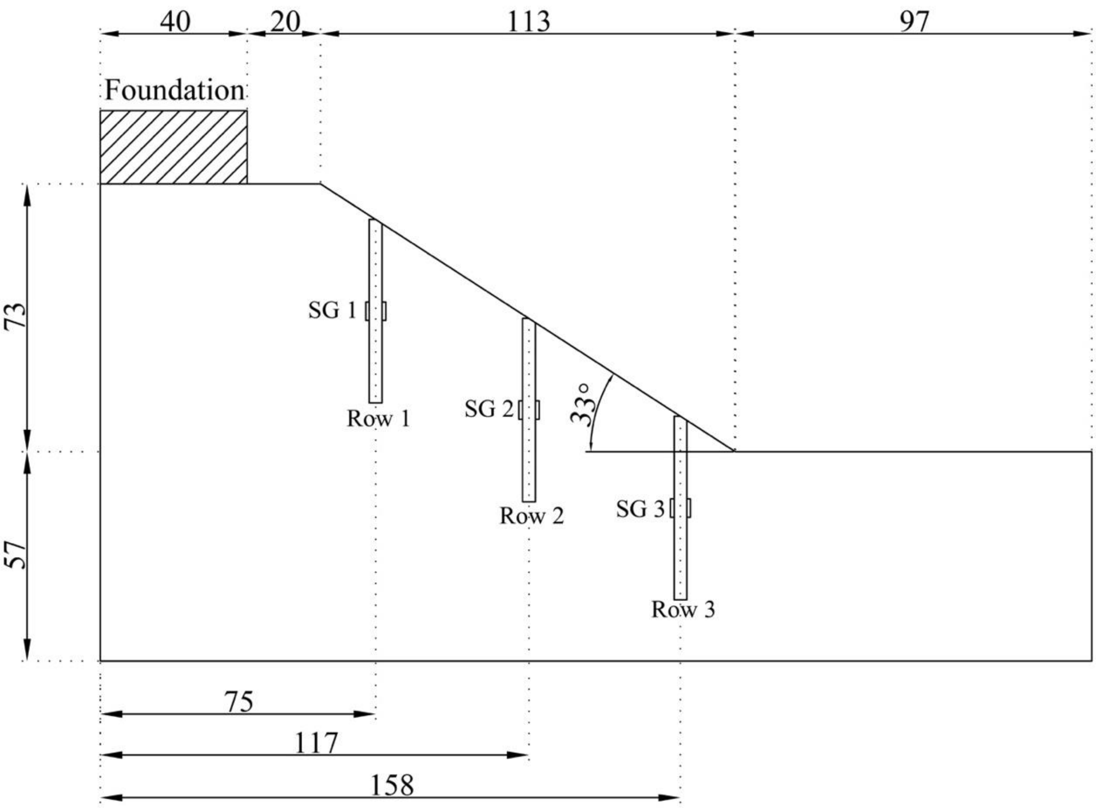

Figure 1 Geometry of the slope in model scale (All dimensions are in mm). SG denotes the position of strain gauge on the instrumented roots

2.1 Soil

Soil used for test was Delft Centrifuge sand. It is a uniformly graded dry sand with a D_{50} of 0.82 mm. Fundamental properties of Delft Centrifuge sand are given in Table 2 (Askarinejad, Sitanggang & Schenkeveld, 2017).

Table 1 Centrifuge scaling law for (From Liang et al. 2017)

QUANTITY	SCALING FACTOR
LENGTH	1/N
STRAIN	1
STRESS	1
FORCE	$1/N^2$
BENDING MOMENT	$1/N^3$

Table 2 Properties of Delft Centrifuge sand

PARAMETER	VALUE
MAXIMUM VOID RATIO	0.72
MINIMUM VOID RATIO	0.52
SPECIFIC GRAVITY	2.65
D_{10}	0.65 (mm)
D_{30}	0.74 (mm)
D_{50}	0.82 (mm)
D_{60}	0.89 (mm)
ANGLE OF RESIDUAL FRICTION	32.5°

Air pluviation was used to deposit the sand to create uniform layers. Density of the model was controlled by changing the fall height, size of the openings and the number of openings in the pluviation apparatus. Increase in fall height, size of the openings and number of openings result in a denser model (Gade & Dasaka, 2017). Models prepared were in a dense state with a relative density of 80%.

2.2 Model roots

Centrifuge tests done previously on root reinforcement were mostly done using real roots of grasses to replicate the behaviour of tree roots (Askarinejad & Springman 2015; Leung, Garg, Coo, Ng & Hau, 2015; Sonnenberg et al. 2010). Problem with using such kind of roots is the inability to repeat the behaviour of one test to another and difficulty in comparing the data of different simulations. To overcome this drawback, 3D printed roots were used in this research. Various materials can be 3D printed. Acrylonitrile Butadiene Styrene (ABS) was used to print roots because mechanical properties of ABS and tree roots were very similar (Duckett, 2013). Mechanical properties of ABS are given in Table 3. Previous test on ABS as roots has been done by Liang (2015) and the behaviour was found to be similar to that of roots.

Table 3 Properties of Printed ABS

MECHANICAL PROPERTIES	METRIC
TENSILE MODULUS	1860 MPa
TENSILE STRENGTH (YIELD)	30.3 MPa
ELONGATION AT YIELD	1.8%

Figure 2 shows the instrumented root. All root stumps were simplified as a cylinder with uniform diameter of 7 mm and length of 50 mm, instead of a tapering root structure to model the stump of the root. Stump plays a vital role in the mechanical reinforcement characteristics of trees. At prototype, diameter and length of root was 0.21 m and 1.5 m respectively. Diameter was chosen in order to have sufficient space for instrumentation and the real trees planted in slopes for reinforcement have a maximum root stump diameter of 0.25 m in prototype (Danjon, Barker, Drexhage & Stokes, 2008). Eis, 1974 and Danjon et al. 2008 says that taproot penetrates soil up to 1.5 m beneath soil surface. And length of taproot was chosen based on literature at a maximum limit in order to ensure that shear failure plane crosses the root.

Roots were installed in the model by hanging them at a predefined height using straws during air pluviation of dry sand. Straws were removed once the sand covered almost 75% of the root length. This was done carefully to prevent any disruption to the model.

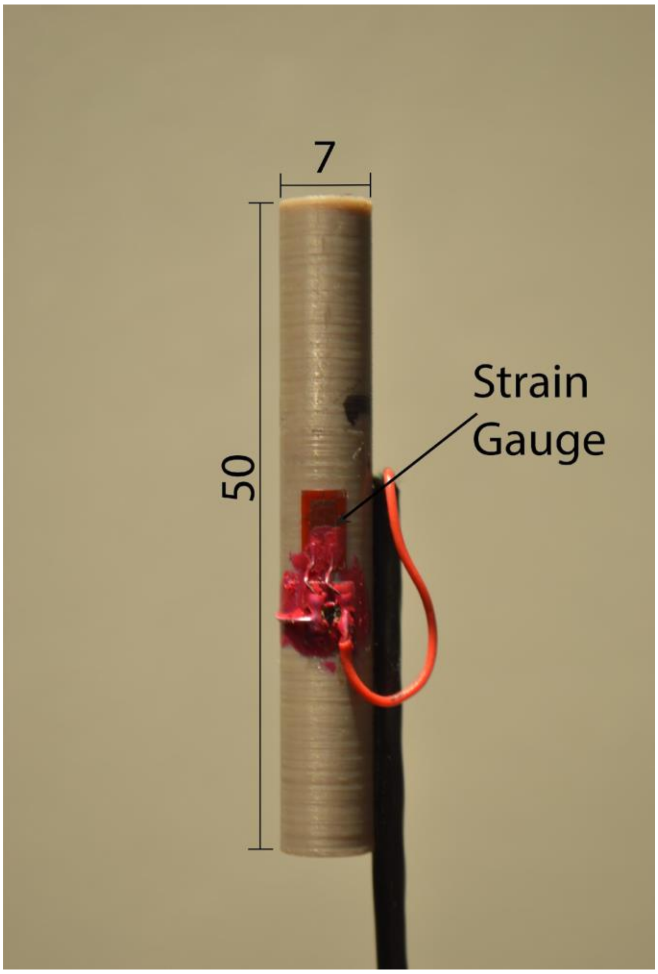

Figure 2 Printed model of instrumented simplified root stump (All dimensions are in mm)

2.3 Model layout

According to previous research (Liang & Zeng 2002), when pile spacing exceeds 8 times the diameter of the pile (8D), piles act as individual piles and group effect is not seen. A spacing of less than 3 times the diameter of pile (3D) is not feasible in real scenario as too many trees in a row can increase the load on the slope. Thus, two models with spacing of S/D = 3 and S/D = 6 were chosen to study the effect of load transfer mechanism and soil arching in slopes. Roots were arranged in a staggered grid as this pattern uses less number of piles/roots and ability to reinforce the slope is similar to matrix pattern. Number of roots in 3D model was 11 and that in 6D model was 5. Plan view of layout is given in Figure 3 and instrumented roots are highlighted. Positions for instrumented roots were chosen carefully in order to avoid the boundary effect.

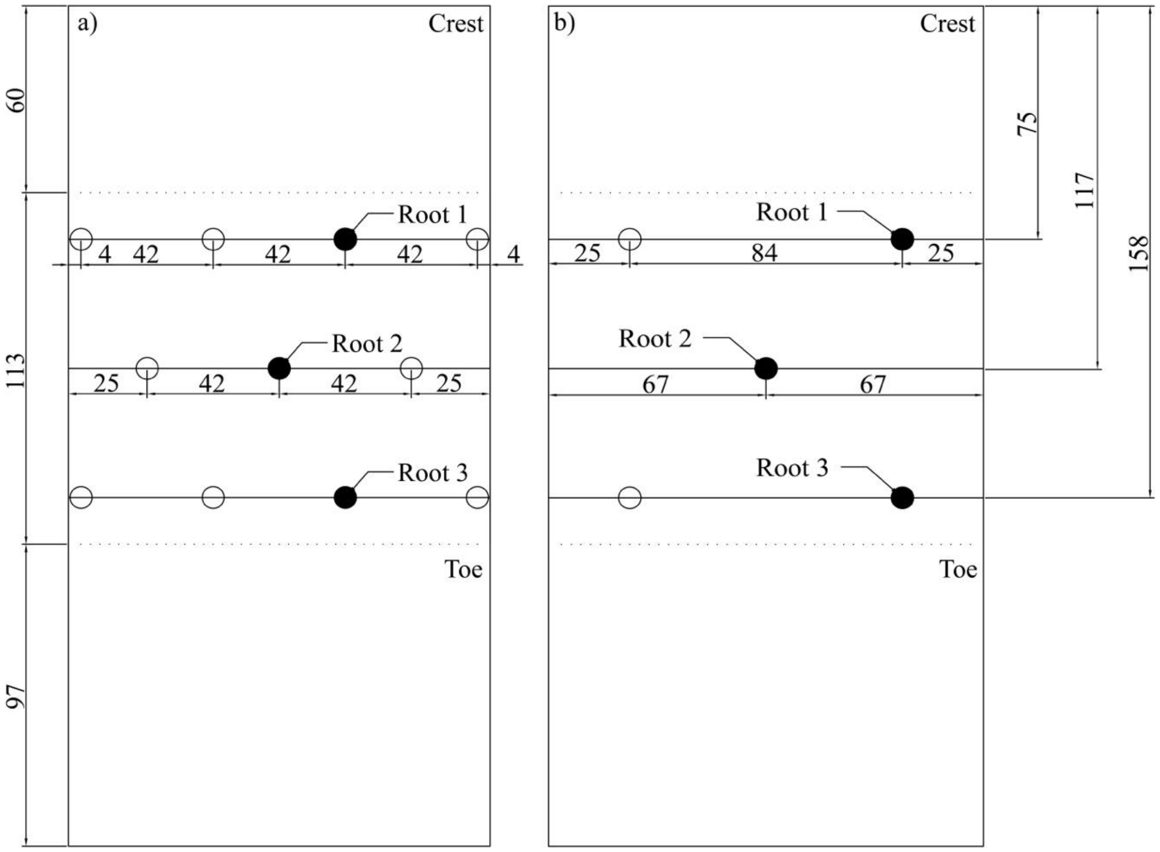

Figure 3 Model layout of a) S/D = 3 b) S/D = 6. Roots 1,2 and 3 are instrumented roots. (All dimensions are in mm)

2.4 Instrumentation

At the center of three model roots, two strain gauges were installed on opposite sides to record the bending strain of the roots. Using bending strain, and knowing the material properties of root, bending moment at the center of the root was calculated. Strain gauges manufactured by RS components having a resistance of 350 Ω were used in order to reduce the error caused by the temperature raise in the centrifuge. To further nullify any error, two resistors were placed on the wire attached to the strain gauge to complete a half bridge Wheatstone circuit. Load cell was used to record the surcharge load induced on the foundation to induce failure of the slope. Load cell consisted of four strain gauges in a full bridge Wheatstone circuit and had a maximum capacity of 4 kN at 5000 microstrains.

2.5 PIV Analysis

Image analysis was done using GeoPIV-RG. GeoPIV-RG is a matlab module which does PIV analysis suitable for geotechnical applications (Stanier, Blaber, Take & White, 2016). In this method, movement of soil with respect to control points on the strong box was measured by forming a mesh in the matlab. Thus, images were taken during the test at an interval of 1 second. Shear plane of failure for the slopes had been determined based on the images. Figure 4 shows an example of result obtained to determine shear failure plane of 3D model.

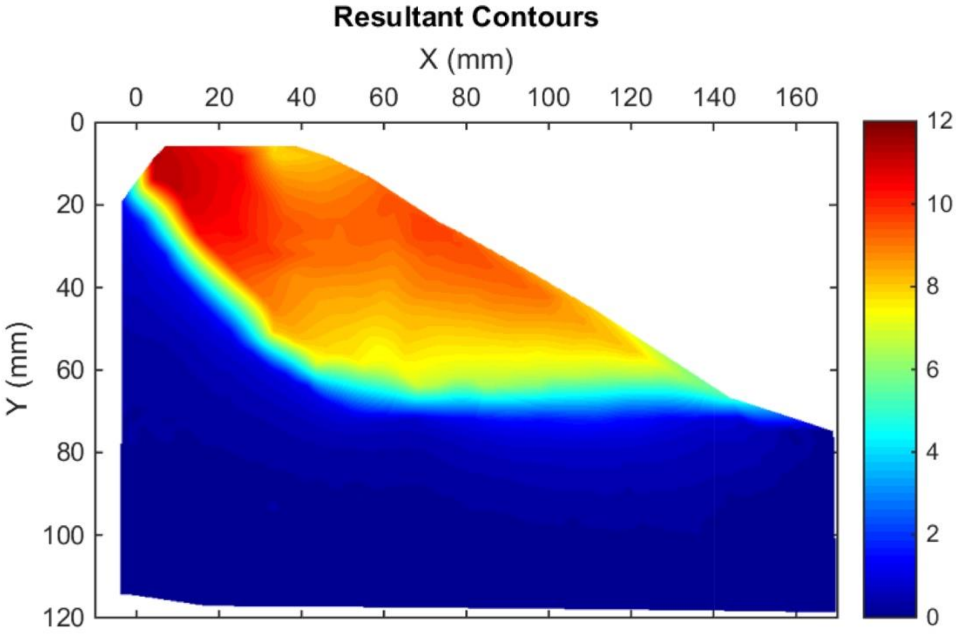

Figure 4 Resultant contours of 3D model obtained from GeoPIV Analysis using Matlab

3. Results and Discussion

At least three tests were done for each model and results were compared and is presented in this section. Comparison of effect of failure and effect of location of shear failure plane on different rows will be explained. For simplicity and better understanding, models with S/D = 3 and S/D = 6 will be mentioned as 3D and 6D models, respectively.

3.1 Load Bearing Capacity

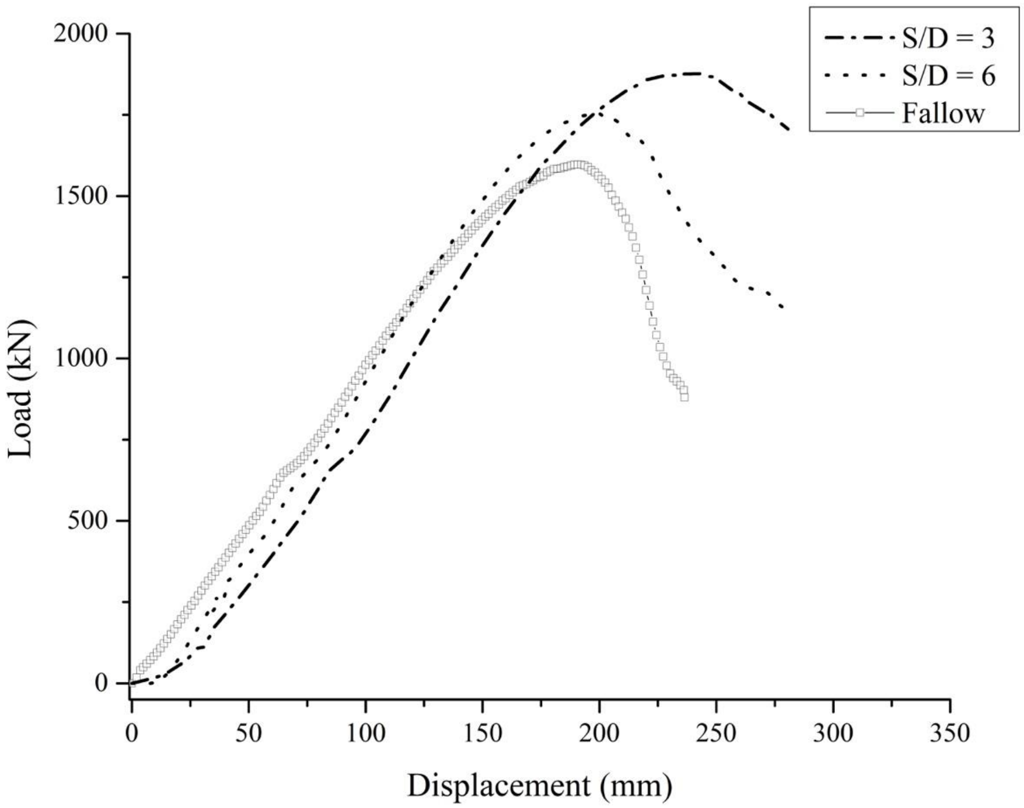

Figure 5 Load displacement plot of models

After the requisite *g* level was obtained, load was introduced on the foundation at top of the slope. Load applied and displacement of foundation were measured and is plotted in Figure 5**.** Load displacement curves for all models have similar pattern. It can also be clearly seen that there is a difference in load bearing capacity between fallow slope and reinforced slopes. Maximum load withstood by fallow, 3D and 6D models were 1596 kN, 1756 kN and 1879 kN respectively in prototype scale. In fallow model, failure was resisted and load was bared by friction between sliding and non-sliding zone. As roots were introduced in the slope, load bearing capacity was increased due to the reinforcement characteristics of roots along with friction between sliding and non-sliding zone, and friction between roots and the soil. By comparing the 3D and 6D models, it was noticeable that load bearing capacity of 3D model was better than the 6D model. In addition to this, failure was attained first in fallow slope followed by 6D model and finally 3D model. This phenomenon is due to the presence of better arching effect in 3D model than that in 6D model i.e. 3D model has a better load transfer mechanism than 6D model and thus more load is bared and failure is prolonged.

3.2 Shear Failure Plane

Formation of shear failure plane for each model of slope is shown in Figure 6. It was observed that shape of shear failure plane of both reinforced model is similar and different from fallow model. This could be due to absence of reinforcement in fallow model and hence, the low resistance offered by the slope to failure. Shear plane of 3D model was deeper than that of fallow and 6D model. As the number of roots in 3D model is more, stiffness of the model as a whole is more. The roots along with soil act as a single mass and thus deep-seated shear plane is observed. On the other hand, in 6D model, since only 5 roots are present in the same area, shear failure plane is shallower.

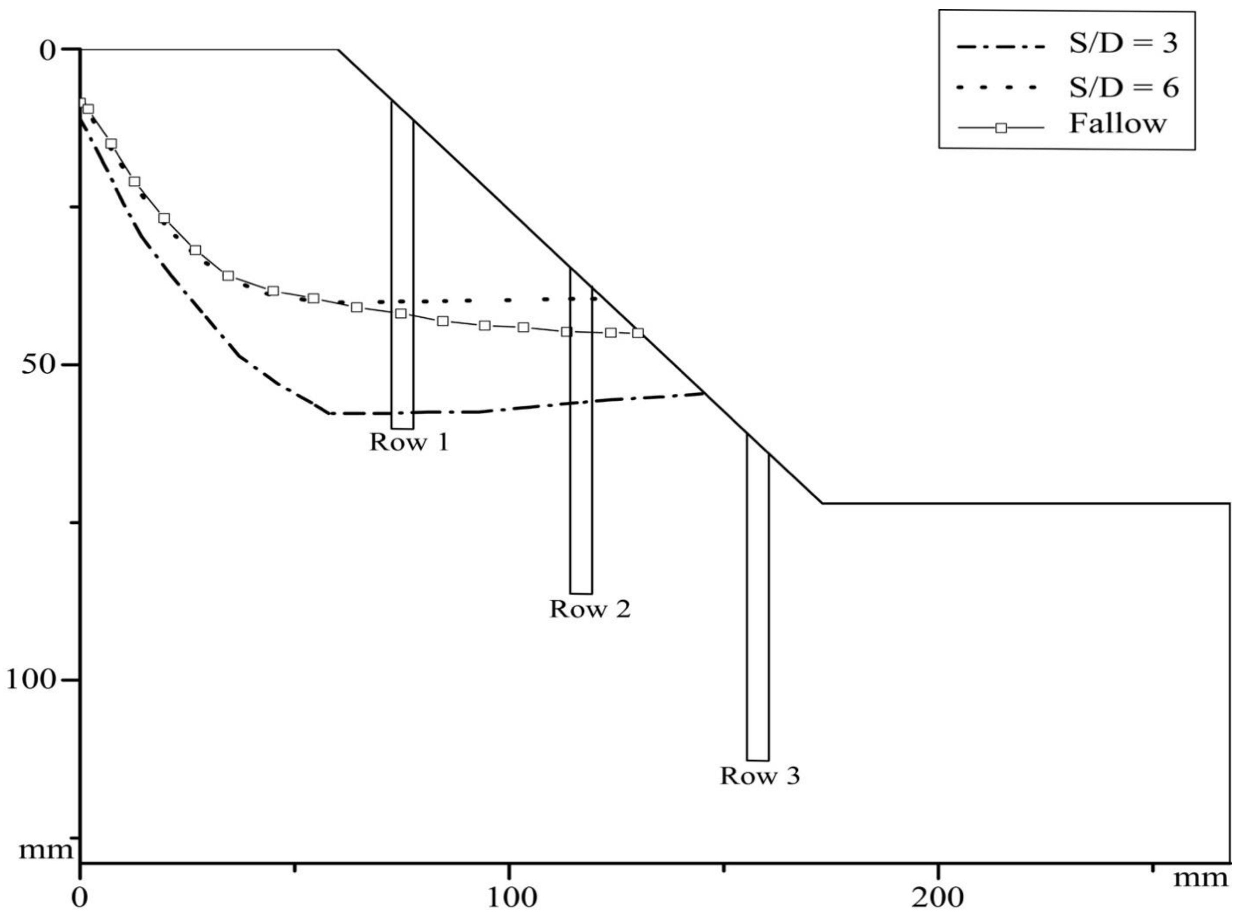

Figure 6 Position of shear plane in all the models. (All dimensions are in mm)

3.3 Effect on roots in row 1

From Figure 7, it can be observed that, for 3D models, shear failure plane crosses roots in row 1 at almost the tip of the root and in 6D models, at beneath the center of root. Since considerable area of root is in the yielding/sliding zone of soil, roots fail either by pull out or rotation. This can be observed by the reduction in bending moment for both models after the peak. Before achieving the peak, bending moment of roots in 3D model is more than that of 6D model. This can be due to the point at which shear failure plane crosses the root in row 1. Also, in 6D model, instrumented root is closer to the boundary than in 3D model. Hence, boundary effects may cause the bending moment to be less in roots in 6D model.

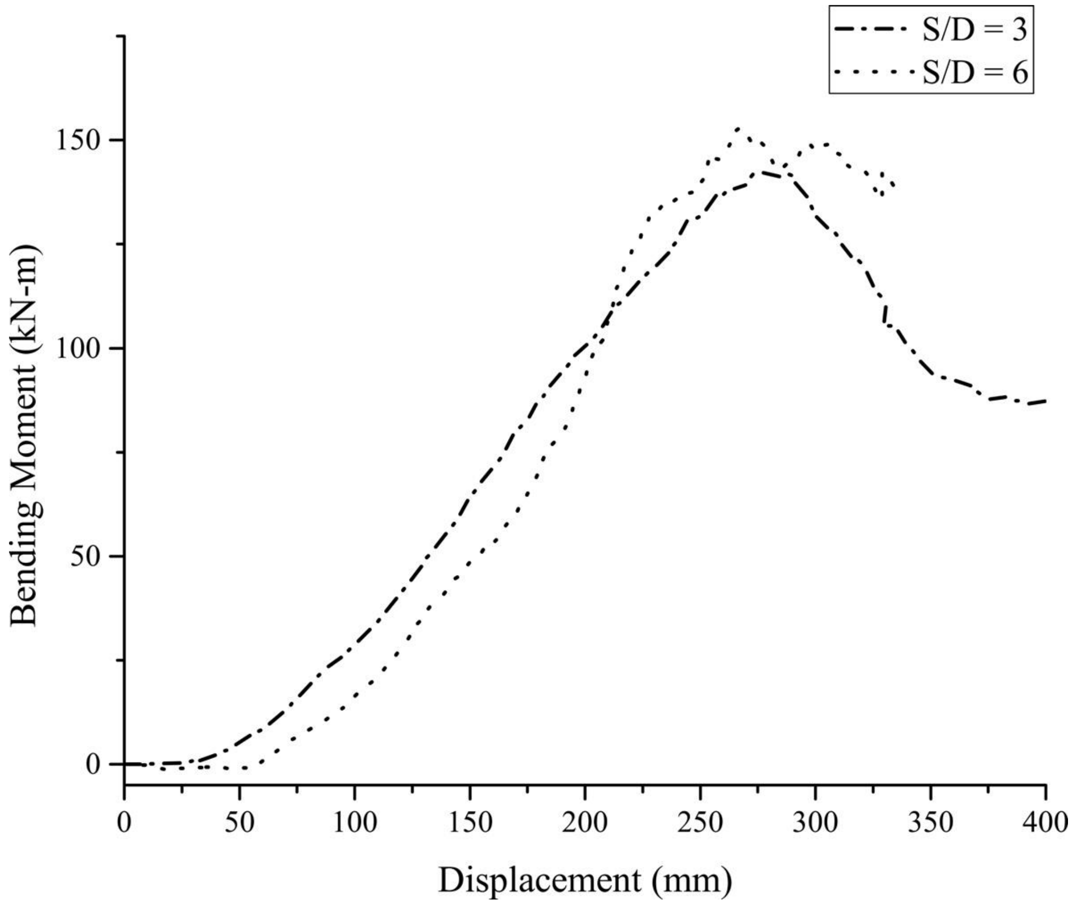

Figure 7 Behaviour of roots in Row 1

3.4 Effect on roots in row 2

For row 2, from Figure 8, it can be seen that bending moment of root in 6D model is greater than that of 3D model throughout the test. From Figure 3, it can be seen that there is only one root in row 2 for 6D model and 3 roots for 3D model. Hence, more load is transferred to the single root in 6D model and almost the same load is distributed among 3 roots in 3D model.

And thus, more bending is witnessed in 6D model. For 6D model, after failure, bending moment remains almost the same after that. This shows that soil arching has fully developed and no more load transfer occurs as soil continues to displace. Test was stopped in 3D model before peak could be attained. This prolonged peak behaviour in 3D model suggests better arching.

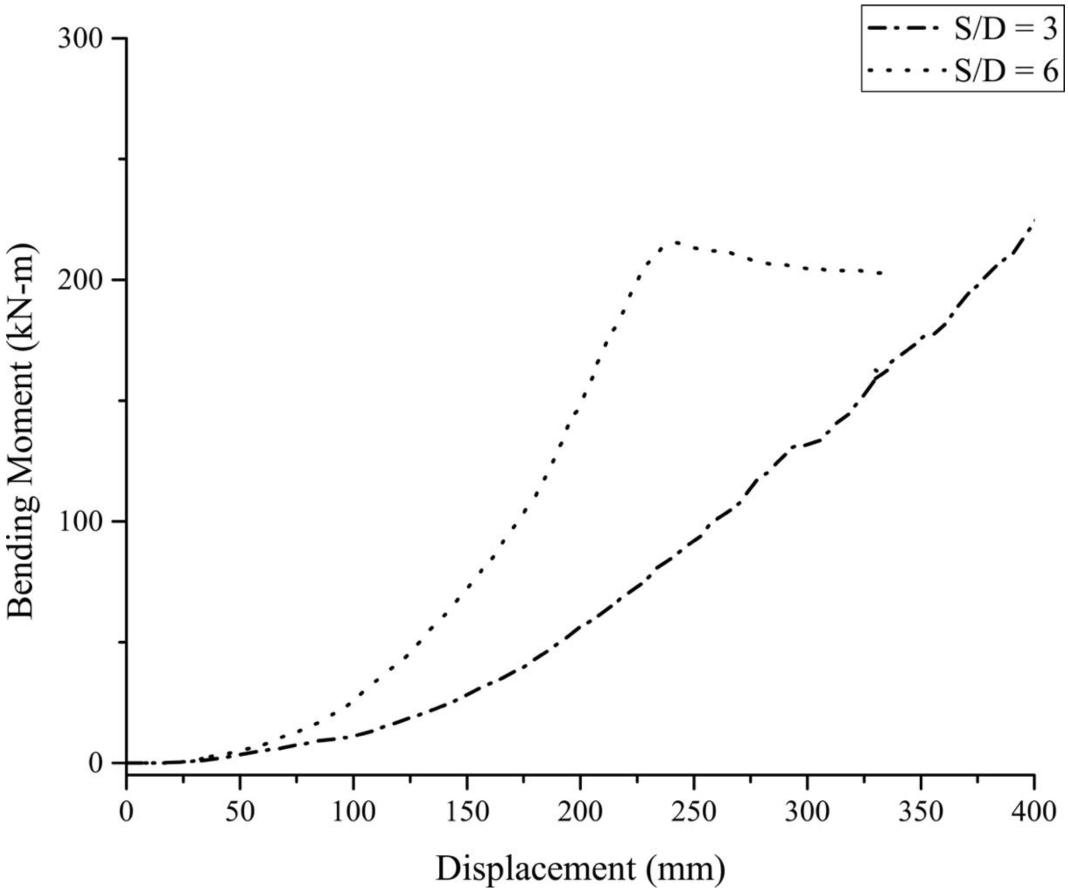

Figure 8 Behaviour of roots in Row 2

3.5 Effect on roots in row 3

It is clear from Figure 9 that bending moment of roots in 6D model is more than roots in 3D model till failure. After failure in 6D model, soil continued to displace, but excess load transfer to the roots was ceased and thus bending moment remained almost the same. This phenomenon can be explained by the presence of soil arching in the slope. Load was transferred to roots in 3D model even after failure was observed in 6D model. 3D model test was stopped before capacity of the root was achieved. This shows that 3D model has better arching and better and prolonged load transfer from yielding to non-yielding part of the slope. It can also be noted that, both the curves in Figure 9 has a transition from convex to concave as the test progressed. This shape behaviour gives an insight whether roots will fail due to rotation or pull out. If transition between convex to concave occurs in the graph, it can be said that root had attained its capacity, and any excess load had no effect on the behaviour of root.

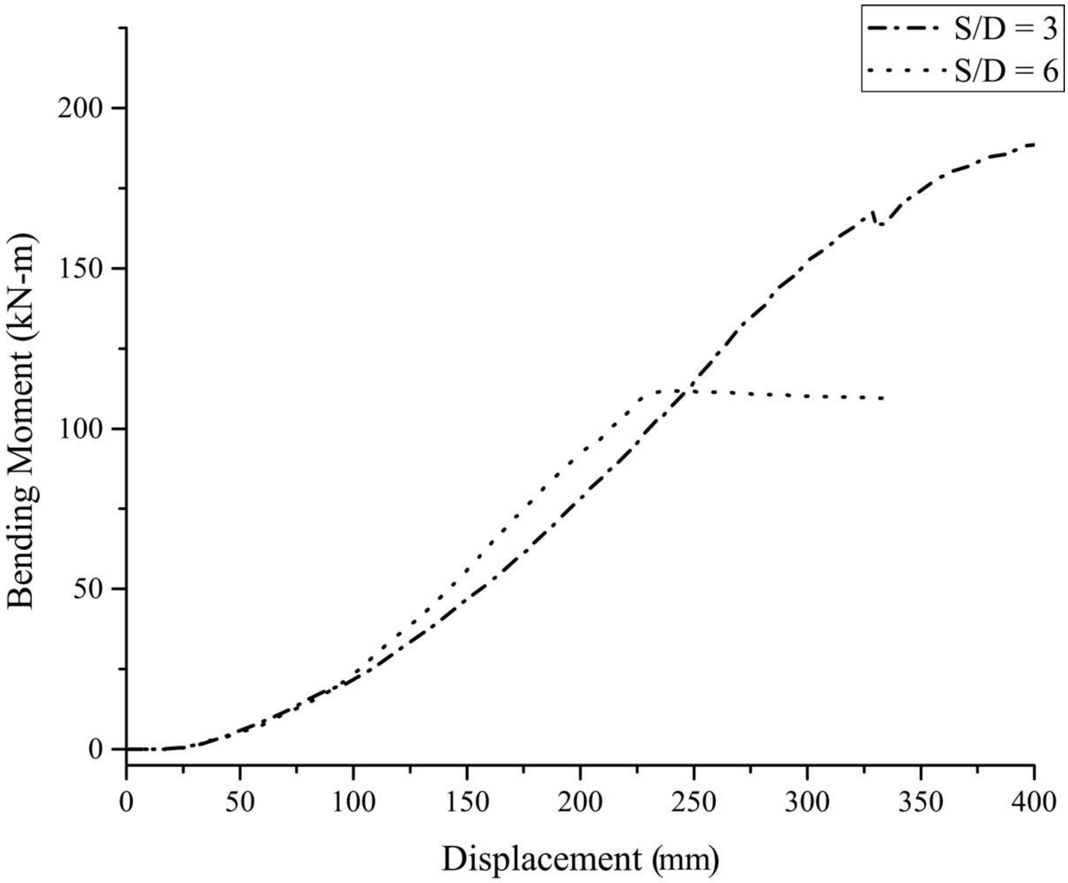

Figure 9 Behaviour of roots in Row 3

4. Conclusions

In this research, roots were arranged in staggered grid on slope and centrifuge tests were conducted to study the effect of spacing of roots on stability of slopes. Root models were planted in dense slope made of dry sand in a strong box. Slope was failed by inducing load on the crest, and load and displacement were measured using a loading frame. Bending strain of roots were measured using strain gauges mounted on the roots. Shear plane of failure for different models of study were obtained from PIV analysis. On comparing various models in the research, following conclusions were made,

- Roots arranged in staggered grid have an influence on the stability of the slope. Load bearing capacity of reinforced slopes were found to be more than that of fallow slopes.
- As spacing of roots increases, load bearing capacity of the slopes decreases and failure occurs sooner.
- From PIV analysis, shear failure planes for different models were obtained. It was noticed that fallow slope had a shear failure plane shape different from that of reinforced slopes. Both reinforced models had a similar shape of shear failure plane but as the spacing decreases, the depth of shear plane increased.
- Strain gauges placed on roots were used to measure the bending strain of roots and bending moment increases gradually as the slope fails. Once the threshold was reached, depending on the position of root in the slope, two scenarios were observed, namely,
    - ➢ If approximately more than 30% of the root is above the shear failure plane, bending moment of roots starts to reduce after peak is achieved i.e. roots fail by either pull out or rotation.
    - ➢ If approximately less than 30% of the root is above the shear failure plane, bending moment of the root remains almost same after failure and no excess load is bared by the roots.
- Roots that were barely in the non-sliding area of the slope failed either by pull out or rotation and thus bending moment of the root was observed to reduce drastically.
- Bending moment of roots that were in the shear failure plane had a curve which is convex in nature and bending moment curves of roots outside the shear failure plane starts as convex but tends to become concave as the test progresses.

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