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Slope Stability Analysis of Soil Nailed Structure by using ASD and LRFD Methods

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Abstract: Many departments where embankments are constructed for highways and railway tracks face the problem of failure of embankments. Safety of the human beings and infrastructure is endangered because of slope failures resulting in loss of life and loss of investment which is a matter of concern in the Government bodies, and disaster relief authorities. These failures impede the socio-economic development of the country. This comprehensive study includes slope stabilization by using soil nails known as reinforcement in soil slopes. In this paper, analysis is carried out for slope stability by ASD (Allowable Stress Design) methods and LRFD (Load and Resistance Factor Design) for various nails inclinations to find out the better nails inclination for better slope stability. By using ASD and LRFD analytical methods the maximum FOS is observed in the range of 15^0 to 25^0 nails inclination.

Keywords: soil nailing, slope stability, ground improvement, reinforced soil, embankment, nail inclination.

1. INTRODUCTION

Engineers and construction experts in different countries like America, Europe, and Japan have been utilizing the unique benefits of soil nailing since the late 1960s. The insitu reinforcement of soils is a geotechnical engineering process that has various types of applications for stabilizing slopes and excavations. Reinforced soil is an advanced composite material made up of soil and reinforcement. This material is similar to reinforced cement concrete in terms of compressive and tensile strength. The fundamental principles of soil reinforcement can be found in nature. Vidal was the first to use an advanced technique of soil reinforcement in 1969. As per Vidal's theory, the gravitational pull friction is caused by the reciprocal interaction of the reinforcing horizontal members and soil. Using this concept in 1986, in France, the retaining walls were built. Nowadays in developing countries, slope reinforcement techniques are widely used. In the field of reinforced soil, there has been a lot of theoretical development. In France, near Versailles, for the first time, an 18 m high sand cut slope was stabilized in a railroad widening project (Rabejac and Toudic, 1974). Due to the less time required for construction and less expensive than other methods, soil nailing is more suitable. In France and other parts of Europe, soil nailing is more popular. In Germany, a soil nail wall was used first time in 1975. (Stocker et al., 1979).

2. LITERATURE REVIEW

In the analysis/design of a soil nailing structure, the stability or strength of the soil nailing is important. The stability of soil nailing is affected by several factors, including nail properties such as length, spacing, and inclination. The stability of a soil-nailed structure is also affected by soil properties, pull-out strength, grout bond strength, and wall inclination. Many researchers have a look into these parameters. Because of the limited number of parameters and its simplicity, the Limit Equilibrium Method (LEM) is generally used for soil nailed wall stability analysis. Internal stability, external stability, and facing stability are the three major requirements that must be seen in this method. FHWA manual, Davis Method, French method, and German Method, are represented by Byrne et al. (1996), Shen et al. (1981), Schlosser (1981), and Stocker et al. (1979) respectively. By using the Finite Element Method (FEM) Chang (2008) examined the various effective factors in the slope stability analysis. Sivakumar B and Singh V. P. (2011) analyzed the soil nailing retaining wall for vertical cut/support by using 2D FEM, also they designed a soil nail wall based on the LRFD approach. Byene et al. (1998), worked on the use of uniform or variable nail lengths, and he suggested that continuous nails length are suitable in areas where ground moments or extreme displacement does not occur. In 1980, Jewell used a shear box test and identify the effect of soil nails orientation on the shear strength of the soil. It was observed that w.r.t. the nails orientation the shear strength of soil is changed.

3. APPLICATIONS OF SOIL NAIL WALLS:

In excavation applications for vertical or nearly vertical cuts, the soil nail walls are particularly used. End slope removal during retaining structure repair, highway cut stabilization, under existing bridge abutments, underpass widening &

reconstruction, and tunnel portals have all been successfully recognized by soil nailing. The following applications are particularly suitable for soil nail walls, (whether impermanent/temporary or permanent):

- Roadway or Highway cut excavations;
- Tunnel portals;
- Road widening (under existing bridge abutments);
- Hybrid soil nail walls;
- Repair and reconstruction of existing retaining structures;
- SMSE (Shored Mechanically Stabilized Earth) walls.

4. SUITABLE AND UNSUITABLE SOIL CONDITIONS FOR SOIL NAILING

4.1 Favourable Soil Conditions

In an inclusive range of soils, soil nail walls have been established. When favorable soil conditions occur then long-term difficulties and construction problems are commonly avoided. In the two circumstances, soil nailing has proven to be really cost-effective and technically feasible when (1) all soil nails are situated above the GW (groundwater) table within a cross-section, and (2) The face of the excavation does not adversely affect the groundwater (GW) if the soil nails are underneath the GW table then the bond strength interfaces among the grout and the adjacent/surrounding soil. (Source FHWA0-IF-03-017).

Based on the favorable conditions noted above, for soil nailing applications, suitable ground types are

4.1.1 Stiff to hard fine-grained soils: in these types of soil, silty clays, stiff to hard clays, sandy silts, sandy clays, clayey silts, and combinations thereof are found.

4.1.2 Dense to very dense granular soils: in this category, if sand and gravel are built-in with SPT, N-values greater than 30 (Terzaghi et al., 1996), and with some fines or cohesion provided with frail natural cementation. Capillary forces in saturated fine sands provide a superficial cohesion.

4.1.3 Weathered rock: weathered rock where no weak planes are found may be a good supporting material for soil nails as well as there are no weak planes in unfavorable locations (for example weak planes tumbling into the excavation).

4.1.4 Glacial soils: These soils are characteristically dense, the limited amount of fines with well-graded granular materials, glacial materials, and glacial outwash are typically suitable for soil nailing applications.

4.2 Difficult / Unfavourable Soil Conditions (Source FHWA0-IF-03-017)

Unfavorable soil types examples and ground conditions are:

4.2.1 poorly graded and Dry cohesionless soils: When coarse-grained non-cohesive soils are completely dry, have no fines, or have no natural cementation property, apparent cohesion is not present. As a result, it’s very difficult making the required vertical or closely vertical cuts.

4.2.2 Soils with high groundwater (GW): At the back of the soil nail wall, resting on groundwater will necessitate extensive drainage, in this location stabilization of the mass of the soil is required. Furthermore, the large amounts of GW collapse soil nail holes easily, especially in loose granular soils. The shotcrete application may be difficult due to excessive groundwater seeping out.

4.2.3 Soils with cobbles and boulders:

in the soil, a large number of boulders and cobbles make drilling difficult, due to this, significant construction delays and increases in costs of construction. When only a few cobbles or boulders are existent, in this case, the drilling orientation changed from location to location and may reduce or remove the majority of the difficult drilling. But when there are too many boulders, this approach has practical limitations.

4.2.4 Fine-grained soils (Soft to very soft): In lenient fine-grained soils, at the excavation's bottom the possibilities for instability are high. for highly plastic soil, the long-term soil deformations may be a concern i. e. the creep of soil. In temporary applications, the creep deformations are generally less.

4.2.5 Organic soils: Organic soils like organic silts, organic clay, and peat have very low bond strength and shearing strengths. These unadvantageous locations may have a maleficent impact on the stability of the wall. For providing stability in the entire structure very long soil nails will be required. As compared to inorganic soils the organic soils tend to be more corrosive.

4.2.6 Highly corrosive soil (cinder, slag) or groundwater: The expensive corrosion protection is required in highly corrosive soils and hence it is more detrimental for the soil-nailed walls structures.

4.2.7 Weathered rock (with unfavorable weakness planes): Grouting is difficult in weathered rock because of a lot of unfavorable weakness planes like faults, joints, shears, fractures, bedding, cleavage, etc.

4.2.8 Loess: in this type of soil at the dry state condition installation of nails is very easy and economical and its exhibits acceptable strength also at dry state. If a large amount of water percolates behind the structure, the loess structure reduces the soil strength and the structure may collapse. The wetted condition may result in extremely low soil shear strengths. In these cases, using traditional nail installation methods may result in unusually long soil nail lengths.

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5 REINFORCEMENT CONCEPT OF SOIL NAILING

The reinforced soil concept is antediluvian. In the ancient period, people used branches of trees, Bamboo, and sticks for reinforcing kaccha houses and retaining the structures also. Thereafter, in the last century; in the early 1960s, the origin of soil nailing developed. At the same time, for the stabilization of slopes, shotcrete, and steel reinforcement have been used. Nowadays soil nailing is a very common method of slope stabilization. Steel bar embedded in cementitious grout called soil nail. It is used to transfer the tensile load from the active zone to the passive zone. Walker, et. al, handled retaining wall (dry-stone) construction stabilized by soil nailing in France and Britain. As compared to the other conventional stabilization techniques, the soil-nailed construction cost is very less. The nail's inclinations affect the efficiency w.r.t. the ruptured surface. The nail element stiffness actions in positions of shearing, tensile, and flexural. These activities will involve the deformation of the soil mass to mobilize the nail strength.

6 CONSTRUCTION SEQUENCE (AS PER FHWA-NHI-14-007 -2015)

A soil nail wall typical construction sequence is mentioned below and shown schematically in Figure 1.

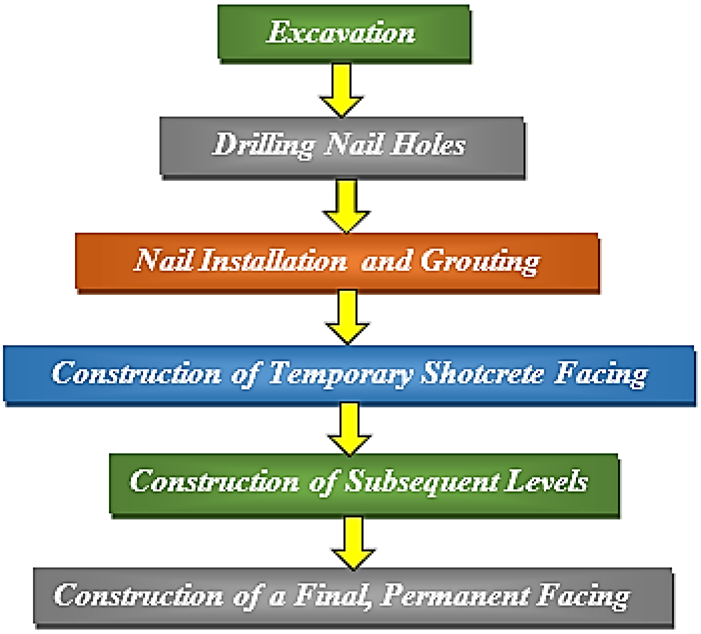

Figure 1. Construction Sequence of Soil Nail Wall

i) Excavation. for unsupported cut, the initial excavation lift (depth) may range between 0.762 m and 2.134 m but is typically 0.914 m to 1.525 m. when the first row of nails will be successfully installed then reached slightly below the next excavation.
ii) Nail Holes Drilling: Drill holes are frequently left in unsupported soil conditions. For the soil nailing, holes are drilled with specialized drilling equipment and it is controlled from the excavated platform.
iii) Nail installation/ Fixing and Grouting: after the holes drill in the structure, the soil nails called tendons are placed into the hole, and the hole is filled with epoxy grout, cement grout, etc. Epoxy grouting is more costly as compared to cement grouting, hence mostly cement grouting is preferred. Under normal or low pressure, or under gravity the nailing holes filled completely.
iv) Strip Drains Installation. On the construction face strip, drains are situated. The strip drains are rolled down to the next excavation lift and placed between adjacent nails.
v) Initial Shotcrete Facing Construction: To the unsupported cut, the initial facing is applied before digging the next lift of soil. 10 cm thick lightly reinforce shotcrete layer is typically used as the initial facing. The nail head is then engaged against the bearing plate with hex nuts and washers.
vi) Construction of Subsequent Levels. Repeat steps for the remaining excavation lifts. The strip drain is unfolded downward to the next excavation lift. Then added a new welded wire mesh (WWM) panel. During this with the previous WWM panel, at least one full mesh cell overlapped. The previous shotcrete lift is continued with the temporary shotcrete.
vii) Final Face Construction: The final facing is built after reaching the bottom excavation, nails have been installed and tested For the final facing Cast-in-place concrete (CIP), prefabricated panels, reinforced shotcrete, or reinforced concrete, may be used. Drainage ditches, Weep holes, and a footing drain are installed to discharge water.

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After excavation, at each lift shotcrete may be applied immediately earlier drilling of the holes, mostly where the stability of the excavation surface is a concern.

7 MODES OF FAILURE OF SOIL NAIL WALL

As per the FHWA0-IF-03-07 – 2015 manual, the modes of failure in soil nailed walls are categorized into three groups (1) External Failure Modes (2) Internal Failure Modes, and (3) Facing Failure Modes are shown in figure (2).

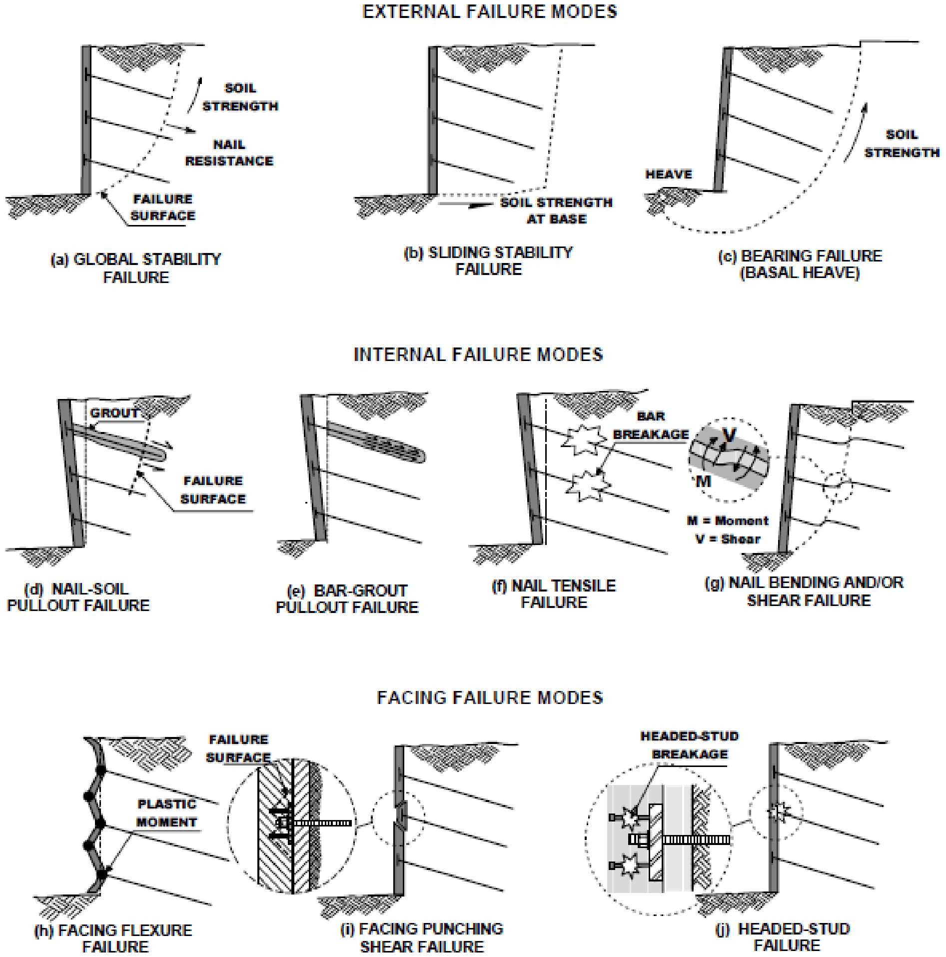

Figure 2: Soil Nail Wall Systems (Modes of Failure)

7.1 External Failure Modes

For external failure modes, the mass of the soil nail wall is treated as a block. For establishing the equilibrium in this block the stability analysis takes place. If one or more soil nails intersects with the failure surface, then the interconnected nails subsidize the block's strength by providing an outer stabilizing force. The three failure modes identified by Byrne (1998) are shown in figure (2)

7.2 Internal Failure Modes

In the soil, nailed wall structure buckling occurs during excavation, and soil nails assemble between the grout and the surrounding soil. Due to the mobilization of nails, tensile forces develop in the surrounding. Due to these stresses developing in the entire structure failure modes can occur. Such as (i) Nails Pullout Failure (ii) Bar-Grout pullout failure (iii) Nails tensile Failure, (iv) Nails bending and/or Shear failure, etc. shown in figure (2)

7.3 Facing Failure Modes

7.3.1 Flexure Failure: in this mode, beyond the flexural capacity excessive bending occurs at the facing of a wall. For this failure mode, both facing (i.e. temporary and permanent facing) should be considered separately.

7.3.2 Punching Shear Failure: this is caused by excessive bending beyond the flexural capacity of the facing. In this failure mode also both facing (i.e. temporary and permanent facing) should be considered separately.

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7.3.3 Headed-Stud (Tensile Failure): This is a failure of the tensioned-headed studs. Only permanent facings are affected by this failure mode.

8. STABILITY ASSESSMENT

In all soil nail improvement projects, the main objective is to increase the FoS to design requirements. In most cases, a slope stability analysis/design is used by the LEM (Limit Equilibrium Method) or SRM (Strength Reduction Method). If there is any surcharge loading, it should be taken into account when determining stability. The intercept of the slip surface and the soil nail determines nail resistance. Individual nail loads should be adjusted for each slip surface when assessing limit equilibrium stability. On slope material strength, the strength reduction method can be used. FEM is used to evaluate the safety factor of stability. In this article, the SSA (Slope Stability Analysis) is carried out by ASD and LRFD methods.

9. ASD AND LRFD METHODS CONCEPT:

FoS is the single factor that taken into account for all design, material, and construction uncertainty. The FoS values are used to calculate allowable values, which represent "working" conditions. In ASD, the design condition is usually expressed as (FHWA. 2015)

$$\sum Q_i \leq R_{all} = \frac{R_n}{FoS} \quad (1)$$

Where, ΣQ_i is the effect of all combined loads, R_{all} is the components allowable stress, R_n is the ultimate capacity of the component, and FoS is the factor of safety.
Currently, an LRFD platform is used to analyze and design transportation structures and substructures. By using LRFD-based methods the results of ASD slope stability must be checked and ensure that all limit states do not cross. To account for uncertainties, for each element the LRFD platform uses both load and resistance factors. The LRFD condition is defined as follows:

$$\emptyset R_n \geq \sum_{i=1}^{N} \gamma_i Q_i \eta_i \quad (2)$$

Where, φ is the resistance factor related to R_n, R_n is nominal resistance, γ_i is the load factor associated with Q_i, Q_i is generic load (or effect), η_i = load-modification factor (equal to 1.0 for soil nail walls).
Various facing resistances, soil nail pull-out resistance, soil shear strength, and Tendon yield strength are examples of nominal resistances.
In ASD platforms, The word strength is more commonly used and nominal resistance is interchangeable. Mean values of other natural materials and nominal resistance of soils to be used in an LRFD platform.

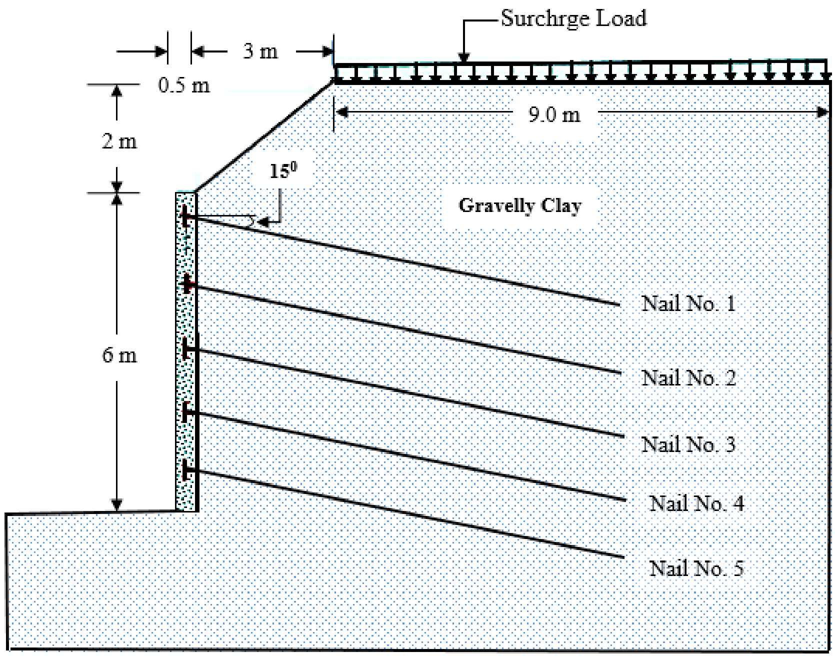

Figure 3 Profile diagram of Soil Nail Wall.

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10 GEOMETRIC MODELLING

Figure 3 demonstrates the geometric model used in this study as well as the slope model's dimensions. The analysis is carried out with various nail inclinations. The geometric boundaries are horizontally constrained on the right and left sides, and the bottom of the geometry is completely fixed. The more user-friendly and versatile GEO 05 2018 software is used for the analysis. Created the geometry of the model first, then assigned the properties of soil, and nails for analysis work. The top surface is subjected to a uniform surcharge load. After all of the properties of the soil and reinforcing bars have been assigned, the stability analysis is carried out to determine the output. The analysis employs the Mohr-Coulomb material model. In the slope, eleven layers of steel bar are reinforced while maintaining the same relative spacing. The ASD and LRFD methods were used to calculate the safety (FoS) factor of slope in GEO5 2008. Table 1 shows the properties of soil and reinforcing bars.

Table 1 Properties of soil and Nails

(a) Soil Properties		**(b) Nails Properties**	
Model	Mohr-Coulomb	Nail Type	HYSD
Type of Soil	Gravelly Clay	Nails Length (L)	9.00 m
Saturated unit weight (γ_{sat})	19.50 kN/m^3	Modulus of Elasticity (E)	2 x 10^5 N/mm^2
The angle of internal friction (φ_{ef})	27^0	Diameter (ϕ)	20 mm
Unit weight (γ)	19.50 kN/m^3	Poisson's ratio (ν)	0.30
Poisson's ratio (ν)	0.35	Minimum yield stress (f_y)	500 N/mm^2
The angle of friction (soil) (δ)	15^0		
The cohesion of soil (c_{ef})	12.00 kPa		

11 COMPARATIVE ANALYSIS BY ASD AND LRFD:

The analysis has been carried out for various nails inclination i.e. 0^0, 5^0, 10^0, 15^0, 25^0, and 30^0 one after the other and the output obtained:

11.1 Verification of nails bearing capacity

Due to the surcharge load on the embankment, the earth pressure is increased in the entire structure from top to the bottom hence the magnitude of nails force is also varying. Due to this phenomenon, it is observed that the maximum force acts on the lowermost nail and It varies with the nail's inclination. The actual nail bearing capacity is 157.08 kN for a 20 mm diameter of nails, it is greater than the forces observed in nails. The nail forces observed by the ASD method are shown in figure 4 and by LRFD method is shown in figure 5.

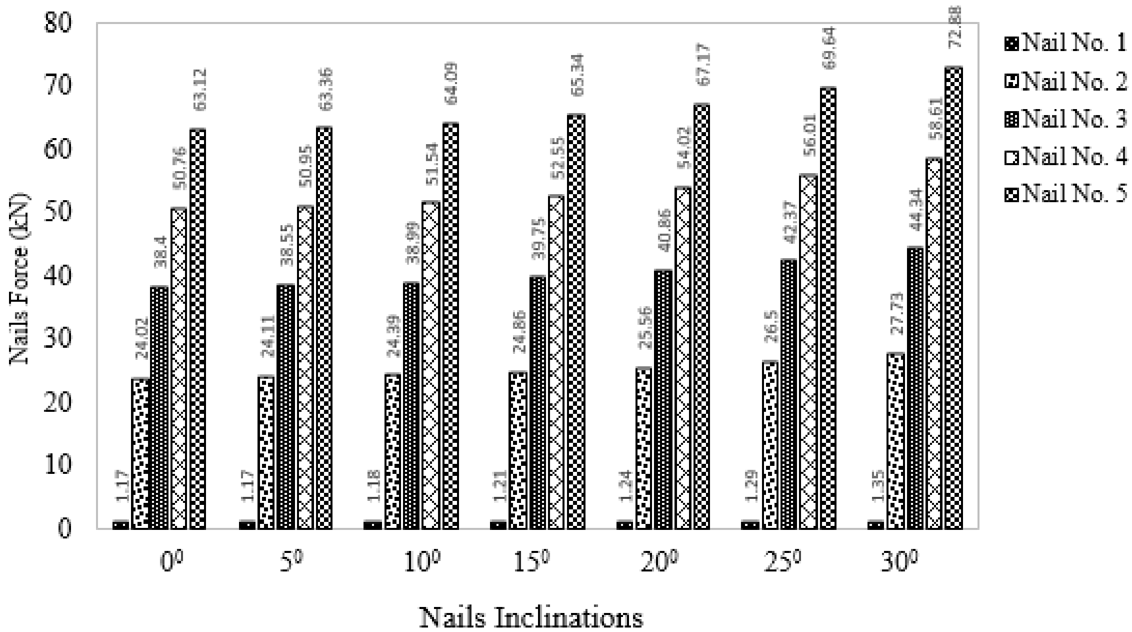

Figure 4 Nail forces observed at various nails inclination (ASD)

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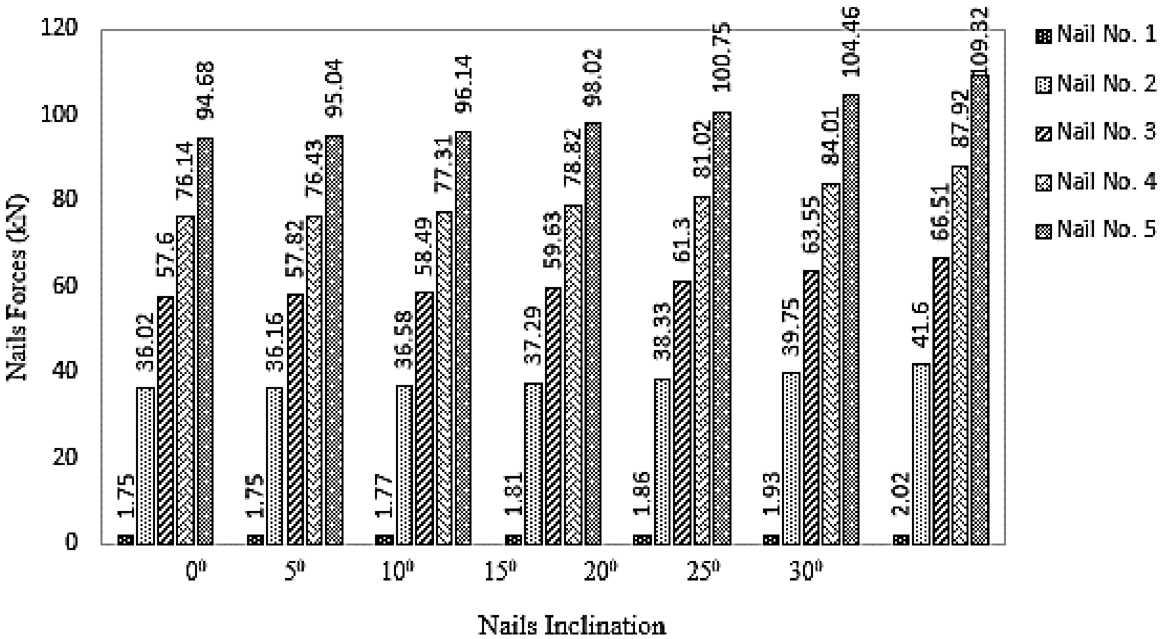

Figure 5 Nail forces observed at various nails inclination (LRFD)

11.2 Slope Stability Verification By Bishops Method

In Bishop Method, the balance of forces considers in vertical directions. This method is based on moments condition. On both sides of the slice, the horizontal forces are eliminated (Bishop 1955). Based on the experience, as per the Fellenius Method, the Bishops simplified method is more precise (Farzin Salmas et. al). In this paper, the slope stability verification has been carried out for ASD and LRFD w.r.t. various nails inclination by Bishop's method. It is found that the maximum FoS is in the range of / between15^0 to 25^0 nails inclination as compared to other nails inclinations described in figure 6.

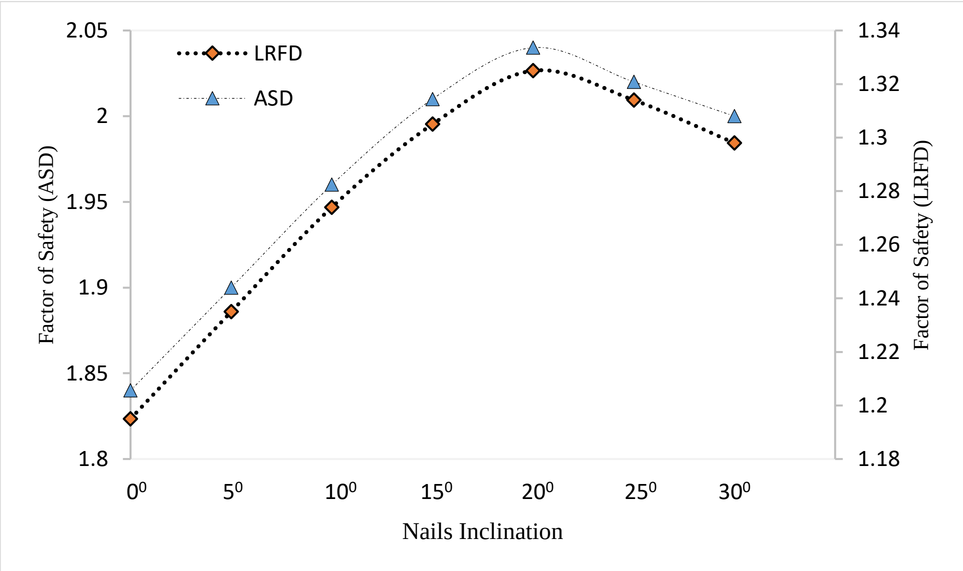

Figure 6 Comparision between Factor of Safety (FOS) by ASD and LRFD

12 CONCLUSION:

As per AASHTO LRFD Bridge design specifications, a 0.75 maximum resistance factor should be used for slopes and a 0.65 maximum resistance factor should be used on slopes for the supporting structures like retaining walls and bridges foundations. where the slope is not directly supporting the structure then the reduced resistance factor is used, but it could impact and damage the structure if slope failure occurs. Small walls which have a minor impact on the stability of established slopes are an exception, and the 0.75 resistance factor can be used in these cases. These 0.75 and 0.65

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resistance factors are similar to 1.3 and 1.5 safety factors, respectively. Overall stability is only evaluated as a service limit state when combined with a load factor of 1.0. When analyzing slope stability for landslide repairs, fills, and permanent cuts, 1.25 is a minimum safety factor that should be used. If there is a lot of improbability in the analysis input limitations, larger safety factors should be used. In the present study, it is observed that due to the pressure increase from top to the bottom the maximum tensile force develop in the bottom-most nail in both analysis i. e. ASD and LRFD. It is also observed that the maximum factor of safety is found at 20^0 nails inclination by both ASD and LRFD methods. In LRFD analysis it is observed the overall structure is not safe at 30^0 nails inclination because the bearing capacity at the foundation is not satisfied. From the overall analysis and LRFD Bridge Design Specifications, the maximum factor of safety was found at 20^0 nails inclination i.e. 2.04 at 20^0 nails inclination by ASD method and 1.33 by LRFD Method. based on the overall analysis it is concluded that the overall global stability of the structure is found at 15^0 to 25^0 nails inclination by ASD and LRFD methods.

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