Analysis of the Behaviour of Improved Soil under Shallow Concrete Foundations

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***Abstract**: As a step towards sustainability and environmental protection, use of waste material and by-products in construction activities is becoming a trend. Quarry dust is a waste product of stone crushing process, which can be effectively used as a shallow ground stabilizer. This research investigates the behaviour of improved soil under a shallow foundation, by adding various mix proportions of quarry dust to the natural weak soil. Further, based on the foundation stability analysis, determining an optimum proportion of soil + quarry dust mix is studied. This is done by numerically analysing the displacement, shear strength, stresses, strains, and safety factors of stabilized soil underneath a shallow foundation. The study confirms that mixing quarry dust with natural weak soil - layered under a shallow foundation can significantly improve the stability of the respective foundation. This is due to the improvement of soil shear strength parameters, i.e., cohesion and friction angle, which are used for the stability analysis in the numerical model – incorporating the Mohr-Coulomb failure criterion. Further, it can be concluded that the optimum quarry dust mix proportion that yields the highest factor of safety of the foundation is around 60% - 80%, in which further increase in quarry dust % can cause reduction in the stability, due to unbalanced effect of cohesion and friction angle of mixed soil. Overall, the study concludes that mixing quarry dust with natural weak soil can be considered as a better ground improvement technique; however, the optimum mix proportion has to be determined after a careful analysis of the the specific soil types, ground conditions and the applied loads.*

***Keywords**: Ground stabilization, Quarry dust, Shear strength, Shallow foundation*

1. Introduction

In the field of Civil Engineering, in certain instances, it is necessary to deal with the improvement of soil, because the in-situ soil properties are not always adequate for the desired construction. The main objective of soil improvement is to improve the engineering performance of the ground and make use of it according to specific requirements. There are several techniques to improve soil, based on construction activity and the type of soil. Some of the most common improvement techniques are soil compaction, vibration methods, re-compression, consolidation, grouting and injection, chemical stabilization, soil reinforcement, use of geo textiles and geo membranes (Kumar and Birdar, 2014; Burland, 1990).

Out of these methods, stabilization of soil by mixing with a foreign material prior to foundation construction is quite important. This method is commonly used in the form of quarry dust, lime, cement, fly ash and sometimes by combining few of above-mentioned forms. These forms help to improve the shear strength of the soil, while increasing its bearing capacity and decreasing settlements, which are essential properties for the stability of a foundation (Caraşca, 2016). The current research focuses on quarry dust as the mixing material to improve the characteristics of natural soil, in which the stability of shallow foundations lying on the improved sub soil layer is studied.

The main reason for choosing quarry dust as the mixing component is that it can be easily obtained through crushers and quarries because quarry dust is a by-product of crushing process (Soosan et al., 2001). The use of quarry dust instead of sand is healthy for the ecosystem, as well as it helps to reduce the cost in the construction field (Marr, 1999). Since the particle size of quarry dust is similar to that of sand, it yields more or less same improvements in mixed soil characteristics, but at a lower cost (Akter et al., 2018). Hence, by adding quarry dust to the natural soil at a certain mix proportion, it is possible to improve soil strength and compaction characteristics, and therefore guarantee the stability of the structures built on it (Onyelowe, 2010; Prakash and Rao, 2017)

In most cases, foundations are constructed using concrete, which in turn creates soil-concrete interfaces at boundaries. The shallow footings fail mainly due to the failure of the soil layer on which the footing is placed. When the load of the superstructure gets transferred to the soil below the footing, it is displaced from its position due to the shear failure of soil as well as ground settlements (Ramads et al., 2010). These types of failures can be duly taken care by improving the engineering properties of the weak soil. Although several studies are conducted on investigating the ground improvement techniques, the behaviour of a shallow foundation and the resultant stability variations on quarry dust - based stabilized soil are not much studied. This behaviour can be varied with different influential factors, especially the characteristics of the mixing material and the mixing proportions.

In this study, an extensive finite-element analysis is carried out using PLAXIS-2D software to comprehensively analyse the stability of shallow foundations lying on improved soil. In fact, the study mainly focuses on the improvement of ground when the sub surface weak soil is mixed with different mix proportions of quarry dust. Important factors pertinent to shallow foundation stability such as total displacements, extreme principal strain, and shear strain, mean and deviatoric stresses and factor of safety values are analysed to assess the stability. Further, the optimum soil: quarry dust mix proportion that yields the highest factor of safety of the shallow foundation under given *in-situ* and loading conditions is assessed through the analysis.

2. Research Methadology

A. Collection of Data

The collection of data for the numerical analysis is done through a rigorous literature review. Properties of quarry dust and natural soil used for the current analysis are tabulated in Table 1 and Table 2, respectively (Sridharan et al., 2006). The soil used for the analysis is basically a dried marine clayey soil as it has very less shear strength in its natural form. The failure criterion of the model was assessed with Mohr-Coulomb material model, which incorporates the cohesion and friction angle values to define the shear strength of soil. The respective shear strength parameters of stabilized soil with different quarry dust mix proportions used in the analysis are shown in Table 3 (Sridharan et al., 2006).

Table 1. Properties of chosen quarry dust sample (Sridharan et al., 2006)

Properties	Quarry Dust
Grain size distribution	
Coarse (2.0 - 4.75 mm) %	8.0
Medium (0.425 - 2.0 mm) %	34.1
Fine (0.75 - 0.425 mm) %	44.1

Silt size (0.002 – 0.075 mm)% Clay size (< 0.002 mm)%	13.9 0
Uniformity coefficient (C_u)	11.1
Coefficient of curvature (C_c)	1.0
Specific gravity	2.80
Optimum Moisture Content (%)	12.6
Maximum Dry Density (kN/m^3)	19.1

Table 2. Properties of chosen soil type (Sridharan et al., 2006)

Properties	Soil Sample
Grain size distribution • Coarse (2.0 - 4.75 mm) % • Medium (0.425 - 2.0 mm) % • Fine (0.75 - 0.425 mm) % • Silt size (0.002 – 0.075 mm)% • Clay size (< 0.002 mm)%	 0 5.1 23 45 21
Liquid limit (%)	73
Plastic limit (%)	36
Plasticity Index (%)	37
Shrinkage limit (%)	21
Specific gravity	2.62

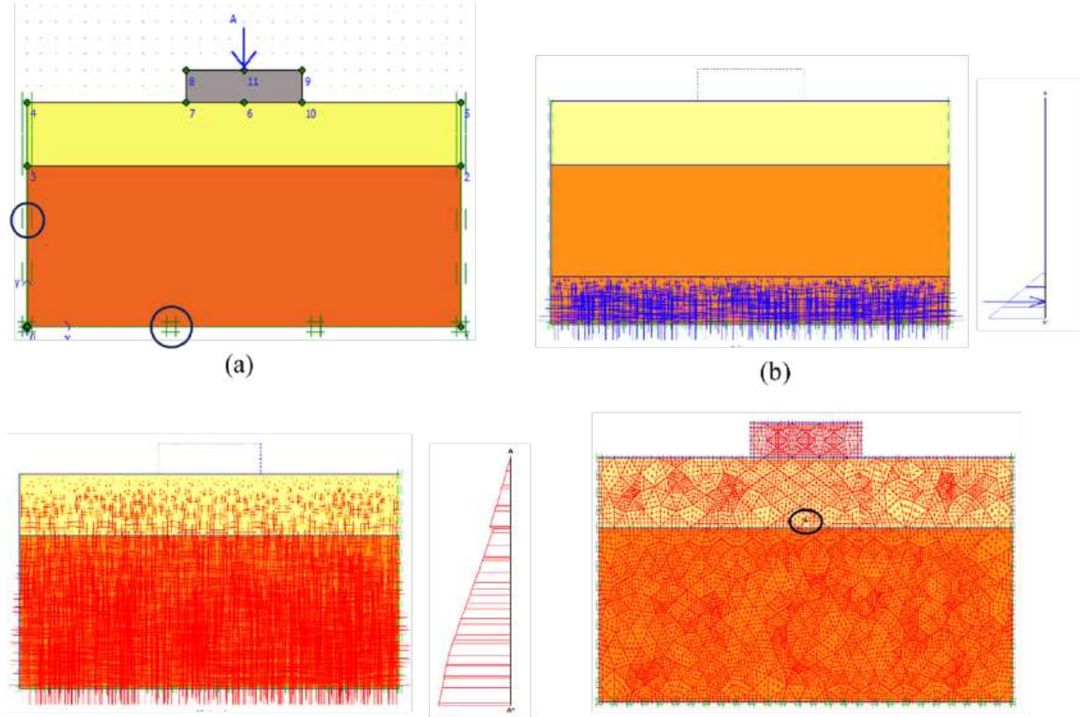
Table 3. Shear strength characteristics of stabilized soil with different quarry dust mix proportions (Sridharan et al., 2006)

Quarry dust mix proportion (%)	**Cohesion – C (kPa)**	**Friction Angle – ϕ (°)**
0	20	15
20	18	19
40	15	26
60	13	30
80	11	35
100	6	43

B. Finite Element Method (FEM)

The model designed in the study is a shallow foundation with 4 m width, sitting on a weak marine clay soil layer. The weak soil layer has a thickness of 2 m and laid on top of the bottom dense sand layer with a thickness of 5 m (see figure 1 (a)). The objective is to test the behaviour of foundation, when the top 2 m layer is improved with different quarry dust mix proportions. This is done by analysing total displacement, shear behaviour and factor of safety, in which the strength parameters of weak soil layer are varied with the experimental data given in section II (A). This will assist in analysing the effect of different quarry dust mix proportions on the stability of the foundation.

A 2-D plane-strain analysis was carried out, where the soil layers were modelled with Mohr-Coulomb material model, during which the cohesion and friction angle values of the topmost 2 m thick layer is systematically varied according to experimental data given in Table 3. This is to simulate the stabilized soil properties under different soil: quarry dust mix proportions. The shallow concrete foundation was modelled with a non-porous linear elastic model. In general, the numerical analysis was carried out as a sensitivity analysis, in which only the strength parameters of the top 2 m weak soil layer were varied, while all the other parameters are fixed. This enables the direct analysis and



(a) (b) (c) (d)

Figure 14. Development of the 2D numerical model

comparison of the effect of strength variation of stabilized topsoil layer on the shallow foundation. As shown in figure 1 (a), the vertical boundaries were restricted from moving to horizontal direction, allowing the simulation of vertical settlements, whereas the bottom horizontal boundary was restricted in moving in both vertical and horizontal directions. The effect of water table was not considered in the current study, in which the phreatic line was defined well below the influence zone of the foundation as shown in figure 1 (b).

The analysis was carried out stepwise, where the 1) initial condition, 2) after construction of foundation and 3) after construction of super-structure (i.e., application of vertical loads) were simulated and the factor of safety values were assessed in each step. This kind of stage-wise analysis in fact enables the analysis of a practical construction sequence of a typical shallow foundation. The total stress distribution at the initial stage (i.e., before constructing the foundation) is illustrated in figure 1 (c), and the point of interest located in the topmost soli layer is shown in figure 1 (d), which is used for the sensitivity analysis and direct comparison of model results.

3. Results and Discussion

A. Foundation settlement analysis

The foundation settlement analysis was done in all the three stages of the construction sequence of shallow foundation as explained in section II (B).

Figure 2 illustrates the variation of the reduction in total settlement (%) of the point of interest selected under the foundation (see figure 1 (d)), against the quarry dust mix proportion (%). This reduction was measured relative to the total settlement of foundation in natural soil, in order to highlight the settlement reductions at different quarry dust mix proportions of stabilized soil. Figure 3 shows the colour maps of total displacement of foundation at 0%, 60% and 100% of quarry dust mix proportions, which clearly shows how the displacement of underlying soil layer occurred at different mix proportions of quarry dust. The results are displayed only for the final stage (i.e., after the application of vertical loads), which is the most critical stage for a shallow foundation construction, compared to intermediate stages, as it gives the highest settlements due to exerted high loads from the super-structure.

In fact, the total settlement includes both vertical and horizontal displacement components, in which the vertical displacement is predominant due to vertical settlement of the foundation upon the applied vertical load. It is evident that the total settlement reduces gradually up to 60 – 80% of quarry dust mix proportion and then increases back at the case of total replacement of weak soil with quarry dust. Therefore, the results convey the idea that in the sense of soil stabilization, the total replacement of natural soil with quarry dust is not always the best option under given in-situ conditions. However, at all the cases, the total settlement of stabilized soil remains less than that of natural weaker soil.

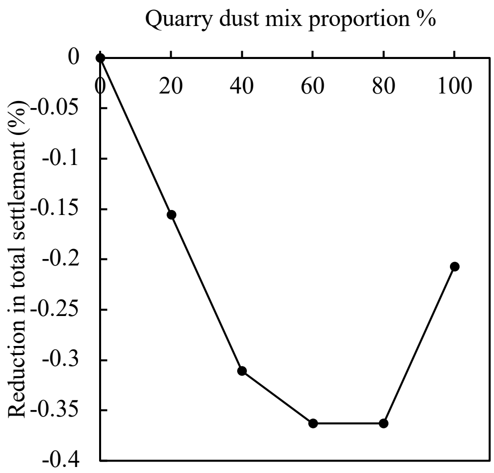


Figure 15. Reduction of the total settlement of shallow foundation with quarry dust mix proportions, relative to the settlemet of natural soil.

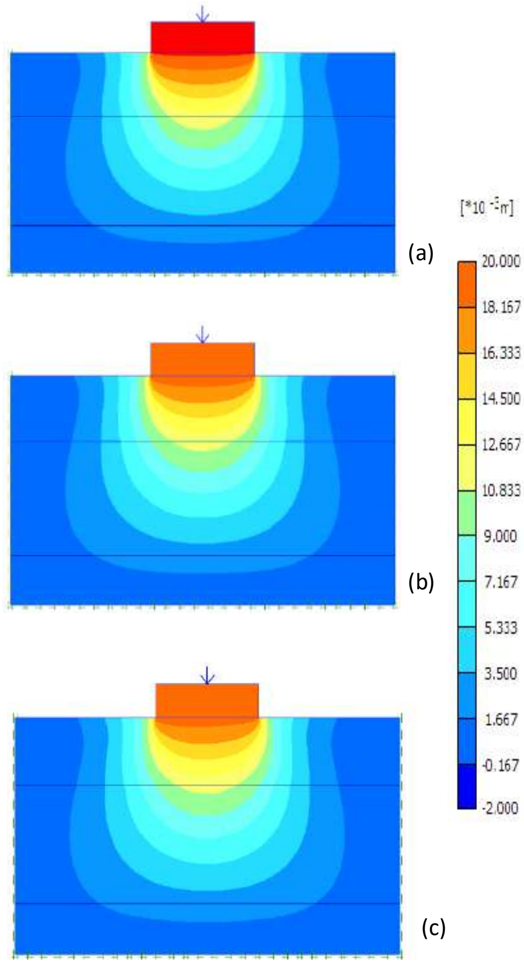


Figure 16. Colour maps of displacement after applying loads on the foundation (a) 0% quarry dust, (b) 60% quarry dust, (c) 100% quarry dust

B. Factor of Safety (FOS) analysis

Application of loads on the foundation, if not the load exerted from the super-structure always increases with the finishing work at the latter stages of the construction project. Also, after completing the construction work, the super-structure loads increase substantially with the addition of both live and dead loads. Therefore, analysis of the factor of safety of the foundation after the application of service loads is critical. The infrastructure should in fact serve the purpose without failure during its serviceability period.

The factor of safety analysis was carried out for stages 2 and 3, as described in section II (B), and the values were directly compared, in order to highlight the importance of considering a proper construction sequence (see figure 4).

As illustrated in figure 4, the factor of safety values were heavily affected after the application of loads on the foundation. In fact, the factor of safety values of the natural weak soil at the 1st phase and 2nd phase are 5.932 and 1.523, respectively, where the reduction is almost 74%. This proves the impact of the applied load towards the safety factors which is one of the main components when it comes to the design process of the foundation. The deviation of 4.409 of the factor of safety value highlights the importance of soil improving and the importance of the level of the improvement.

If the variation of factor of safety with quarry dust % is considered in detail, similar to previous analyses, the factor of safety value increases with the increasing quarry dust mix proportion. The increment has "invert U-shape" behaviour, where the 60% - 80% mix proportion yields the highest possible factor of safety. The further increment of quarry dust causes reduction in factor of safety – conveying a slight reduction in the soil strength, compared to the 80% case. Hence, the analysis suggests that there exists an optimum percentage of quarry dust to be mixed with the natural soil, that yields the highest stability of a shallow foundation.

This is basically due to the variation in soil strength parameters used for the strength analysis, i.e., cohesion and friction angle. In fact, according to Mohr-Coulomb material model, the shear strength of soil is governed by the combination of both cohesion and frictional angle (see Eq. 1).

$$\tau_f = c' + \sigma' \tan\varphi' \quad [1]$$

where, τ_f is the shear strength of soil, c' is the effective cohesion of soil, σ' is the effective normal stress and φ' is the effective friction angle of soil.

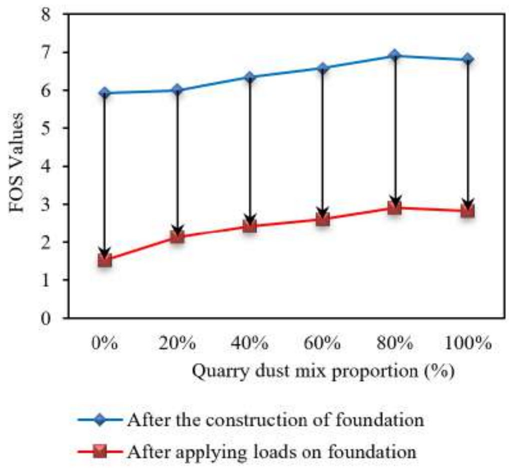


Figure 17. Variation of Factor of Safety of shallow foundation with quarry dust mix proportion, at different stages of construction.

The addition of sandy type quarry dust to the natural weak soil increases its friction angle due to high friction between sharp angular particles of quarry dust. This is the main reason for the initial rapid increment of foundation stability up to 60% of quarry dust mix proportion. In contrast, this simultaneously reduces the cohesion of the mixed soil, as the addition of large quantity of cohesion-less material (i.e., quarry dust) into clayey soil would hinder the cohesive nature of the mixed soil. This imbalance of two strength components will in turn affect the overall shear strength of the resultant mixture.

Hence, the combined variation in the strength parameters ultimately yields an optimum mix proportion, that can be used for the highest stability of the foundation. Hence, it is evident that fully replacement of soil with quarry dust is not the best option in all cases, but there exists an optimum mix proportion that results in the highest stability, with a lesser cost.

4. Conclusion

The current study presents a numerical analysis of the effect of quarry dust on the geotechnical properties of selected weak soil and the resultant effect on the stability of a shallow foundation. Following conclusions were maid based on the findings of the study.

- With increasing quarry dust percentage in the mix, the cohesion of the mixed soil tends to decrease while the friction angle increases, which lead to observe a non-linear variation in the resultant shear strength and thus the behaviour of shallow foundation.
- In fact, the increase of quarry dust proportion in weak soil up to a certain percentage reduces the settlement while increasing the factor of safety of a shallow foundation. According to the current numerical results, the best improvement in stabilized soil in terms of displacement (i.e., settlement) is noticed at 60% - 80% and the highest factor of safety value was noted at 80% mix proportion. However, the factor of safety tends to slightly decrease when the natural soil is completely replaced by the quarry dust – i.e., at the 100% quarry dust mix proportion.
- This is basically due to the combined effect of cohesion and friction angle of stabilized soil, in which the imbalanced contribution of each component (i.e., from natural soil and quarry dust) has resulted in a slightly lower shear strength, yielding a lower factor of safety value.
- Hence, it is evident that fully replacement of soil with quarry dust is not always the best option but it has to be evaluated through a rigorous analysis.

Although, the optimum soil + quarry dust mix proportion is obtained as 60% - 80% in the current analysis, the proportion can be varied with many factors such as in-situ soil properties, quarry dust properties, ground condition, type of structure and the applied load. Hence, a detailed analysis should be carried out considering all the influential parameters, before deciding the optimum quarry dust percentage for a given construction.

Although, the conclusions are replicated in the experimental analysis found in literature, the most important aspect of shallow foundation design (i.e., factor of safety) has to be critically evaluated to assess the level of stability of the foundation. Hence, this study confirms that the stability level varies with the soil+quarry dust mim proportion and should be analysed in detail considering the given situation, incorporating experimental, numerical and analytical assessments.

References

Akter M. S., Jamal M., Ali M. F. and Ahmad N., 2018. 'Effect of Quarry Dust on Different Properties of Soil'. i-Manager's Journal on Future Engineering and Technology, 13(4), p.14.

Burland J. B., 1990. "On the compressibility and shear strength of natural clays". Géotechnique, 40(3), pp.329-378.

Caraşca, O., 2016. "Soil improvement by mixing: techniques and performances". Energy Procedia, 85, pp.85-92.

Kumar A. and Biradar K., 2014. "Soft subgrade stabilization with quarry dust-an industrial waste". International Journal of Research in Engineering and Technology, 3(08), pp.409-412.

Marr W. A., 1999. "Effective uses of Finite element analysis in Geotechnical Engineering". Civil Engineering Practice-Boston, 14(2), pp.89-98.

Onyelowe Ke C., Okafor F. O. and Nwachukwu D., 2010. "Geophysical use of quarry dust (as admixture) as applied to soil stabilization and modification-a review". ARPN Journal of Earth Sciences, 1(1), pp.6-8.

Prakash K. S., Rao C. H., 2017, "Strength characteristics of quarry dust in replacement of sand". In IOP Conference Series: Materials Science and Engineering (Vol. 225, No. 1, p. 012074). IOP Publishing.

Ramadas T. L., Kumar N. D. and Aparna G., 2010, "Swelling and strength characteristics of expansive soil treated with stone dust and fly Ash". In Indian geotechnical conference-2010, GEOtrendz (pp. 16-18).

Soosan T. G., Jose B. T. and Abraham B. M., 2001. "Improvement of ground and highway sub-bases using quarry waste". Proceedings of international seminar on civil engineering,, 730-737.

Sridharan A., Soosan T. G., Jose B. T. and Abraham B. M., 2006, "Shear strength studies on soil-quarry dust mixtures". Geotechnical & Geological Engineering, 24(5), pp.1163-1179.