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Analysis of Dam Foundation in Alluvial Deposits

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Abstract
This paper presents a study made to analyse a gravity dam foundation on alluvial deposits. Alluvial deposits consist of fine fraction and coarse fraction which can be characterised as boulder mixed soil. The percentage fines fraction of alluvial deposits has direct impact on the engineering characteristics of soil including density compactness and consequently affect the stability of Gravity dam in alluvial deposits. In this paper, a relation is established between the percentage of fines fraction with the bulk modulus of elasticity, shear modulus of elasticity and density. This relation is used to predict the mechanical parameters after the improvement of soil with consolidation and compaction grouting which decreases the percentage of void with fines.

FDM software is used for the analysis and stability of gravity dam at full reservoir conditions. The effect of the mechanical parameters for the stability of gravity dam is analysed. The soil material is modeled as homogeneous and heterogeneous material consisting different fraction of boulders and fines. The results from FDM analysis demonstrated the decrease deformation in dam foundation with the decrease in percentage fine fraction in alluvial soil.

Keywords
Alluvial deposits, Fine fraction, Coarse fraction, Gravity Dam, Displacement

1. Introduction

The various types of dams according to method of construction are earthen, rockfill, hardfill, and gravity dam. Usually gravity dam is constructed on stronger soil having hard strata whereas earthen dam is constructed on weak foundation. But in recent times, at Gerdebin dam, Iran there is weak and soft alluvial deposits beneath it and rockfill dam was constructed above it[1]. In Clear lake dam, gravity dam was constructed above alluvium deposits of cobble, boulder, gravel, sand, silt, clay with proper design of filter materials, seepage control mechanism, grouting materials [2].

The significant variations in thickness of the alluvial deposits and the presence of a low strength layer are the major problem to consider for design of dam on alluvial deposits [3] [4]. There's always remain a possibility bed rock can't be found that is why dam has to build within the alluvial soil layers. Treatment of dam foundation in an alluvial deposit is of importance due to being susceptible to the large settlements, which may cause the dam body subjected to undesirable deformations and even, catastrophic failure[1]. The cost of treatment might be extremely difficult and costly.

Rivers in Nepal pass through deep gorges with full of sediments and alluvial deposits. The bed rock might be buried beneath more than 100m below the river bed In such cases the construction of dam foundation on the bedrock is extremely costly especially for small hydropower projects. This subject is not studied in detail in Nepal few dam builds are either directly build on top of bed rock. The risk of dam stability due to deformation in an alluvium and colluviums deposits is to be studied in detail to assure the long-term stability of dam and to protect from the sudden catastrophic failure. Therefore, a study to determine the methodology of accessing the stability of dam in alluvial foundation is necessary.

In this paper, FDM software is used for the analysis of foundation stability of gravity dam at full reservoir conditions. The effect of the mechanical parameters for the stability of gravity dam in alluvial foundation is analysed. The model incorporates the methodology to increase the strength of alluvial soil foundation from the combination of consolidation and compaction grouting. 2D finite difference software is used to determine the, deformation, pore pressure, and stress distribution within the foundation.

2. Dam in Alluvial Foundation

Construction and design of dam on alluvial deposits is a great challenge due to the unpredictability nature of material below. Erosion of fine-graded soils through seepage can cause piping. It will result in differential settlement and seepage of dam. Moreover, alluvial deposits consist of mixtures of boulders, cobbles, gravels, silts, coarse sand, fine sand etc. The finer material between the boulder and cobbles can erode in the presence of high-gradient flow known as suffusion thus resulting the sinkholes in foundation of dam and abutment [5]. Alluvial deposit is a mixture of soil such as clay, silt, sand, gravel and boulder which has been eroded and carried by fast flowing streams and later settled when the velocity of flow decreases [6]. The schematic diagram presented below (figure:1) shows the structure of alluvial soil mass. The Fine fraction is defined as the volume of fine particles except boulder and gravel in an alluvial deposit. It consists of sand and silt. The Coarse fraction is the volume of boulders and gravels in an alluvial deposit which can be extracted as a core from drilling.

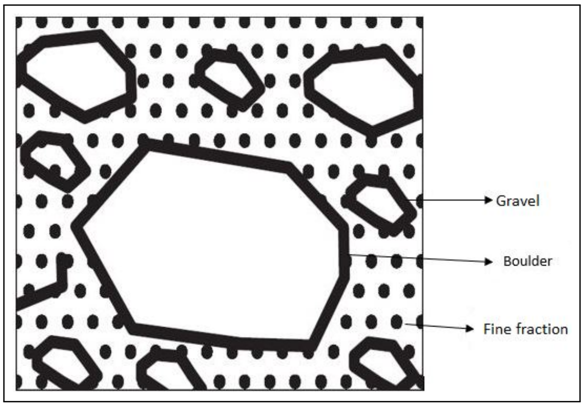

Figure 1: Alluvial mixture containing Boulder,Gravel and Fine fraction.

Skhalta Dam is located in south-west Georgia (Pawson and Russell 2014). Due to landslide and erosion there occurs deposition of alluvial sand, gravels and sediments.And the predominant material contains alluvium and lacustrine deposits. At center of valley 50m thick alluvial soil is deposited. To curtail the quantity of grouting faced symmetrical hardfill dam is selected due to its minimal base area. A research was conducted on “Clear lake dam” having heterogeneous deposits of boulders, cobbles, rockfall, alluvium and lacustrine deposits proposed a solution to minimize cracking, control seepage, and bearing capacity on existing condition (Monley et al. 2018). The primary difficulties in the design was supporting dam on the weak alluvial deposits, controlling seepage gradient, and proving proper filter and drain system at different portion of dam. A roller compacted dam with proper control of seepage gradient, filter drainage system, cutoff wall is constructed to withstand in weak foundation. Another case study was done at Chapar-Abad dam which have alluvial deposits of over 60m thickness as base material and having various coefficient of permeability (Uromeihy and Barzegari 2007). Probable seepage on foundation was estimated by conducting in-situ tests, and numerical modelling. Based on those results installation of grout curtain was suggested.

3. Data Collection and Analysis

The 60m depth borehole data of Kimathanka Arun Hydroelectric Project is collected. It is found that up to 60m depth there is no presence of bed rock. The borehole data shows the lithological characteristics of subsurface which is predominantly consists of sands, gravel, boulder of varying size. And also, the sub-surface geological condition of the project area done by multi-channel analysis of the surface waves (MASW) at major structural sites of the project is collected. MASW calculates the shear wave velocity profile of sub-surface ground condition. Based on shear-wave velocity profile, the dynamic parameters of soil: density, moduli of elasticity of each layer can be estimated. From the 60m depth of borehole log, the distribution of percentage finer fraction and percentage coarse fraction per meter of layer is found out. Then, the percentage finer fraction of borehole log is compared to shear wave velocity profile of MASW survey. For this, exact coordinate of MASW profile and borehole log is scrutinized. And also, average of seven different shear wave velocity profile of MASW survey and borehole log is examined. In these two cases, there was not much variation in the percentage finer content relation with shear wave velocity. From this, the relation of percentage finer fraction with bulk modulus of elasticity, shear modulus of elasticity and density is found out. Deformation and seepage on foundation material is calculated. The below figure 1, 2, 3 illustrates the relationship of Percentage fine fraction with moduli of elasticity and density in an alluvial deposit.

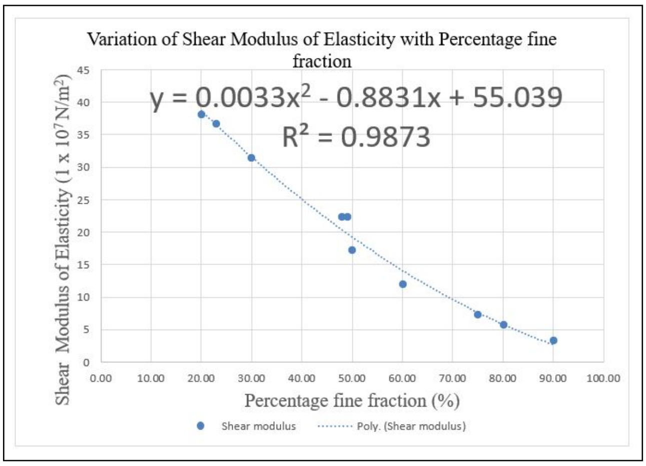

Figure 2: Variation of Shear Modulus of Elasticity with Percentage Fine Fraction in an Alluvial Deposits.

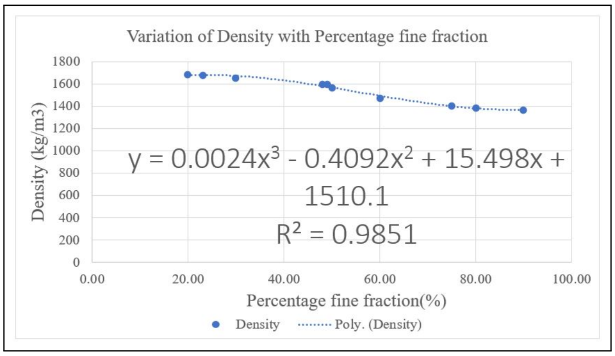

Figure 3: Variation of Density with Percentage Fine Fraction in an Alluvial Deposits.

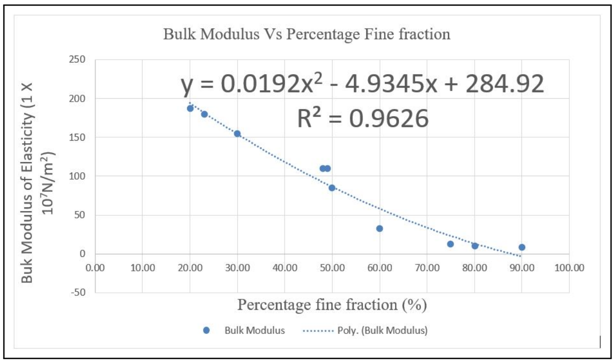

Figure 4: Variation of Bulk Modulus of Elasticity with Percentage Fine Fraction in an Alluvial Deposits.

The material modelling of heterogeneous material is performed. For this the depth and width of foundation material considered is 30m and 60m. At 80 percentage fine fraction, 35 percentage fine fraction and 20 percentage fine fraction, the random heterogeneous material modelling is done. The density and dynamic properties of soil is shown from figure 5 to figure 10.

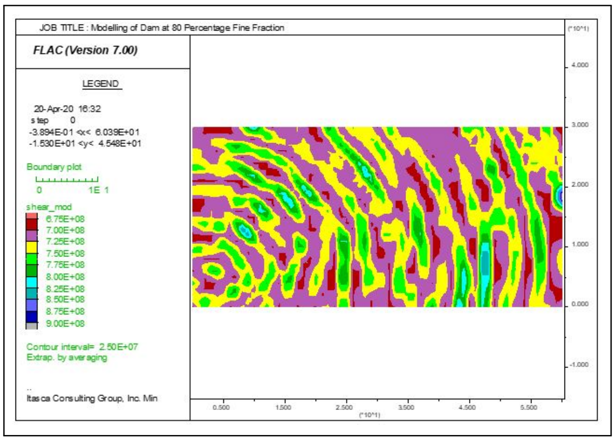

Figure 5: Shear Modulus of Foundation Material at 80 percentage Fine Fraction.

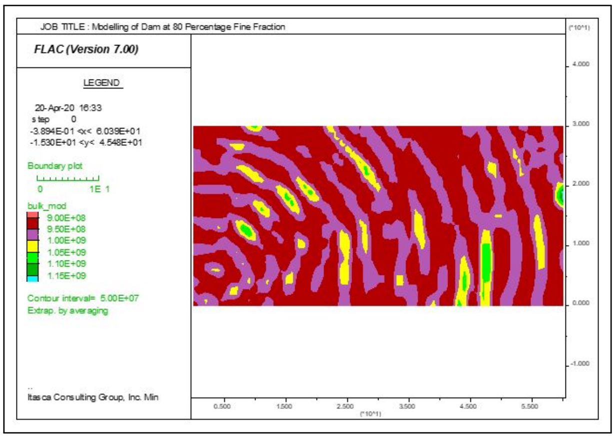

Figure 6: Bulk Modulus of Foundation Material at 80 percentage Fine Fraction.

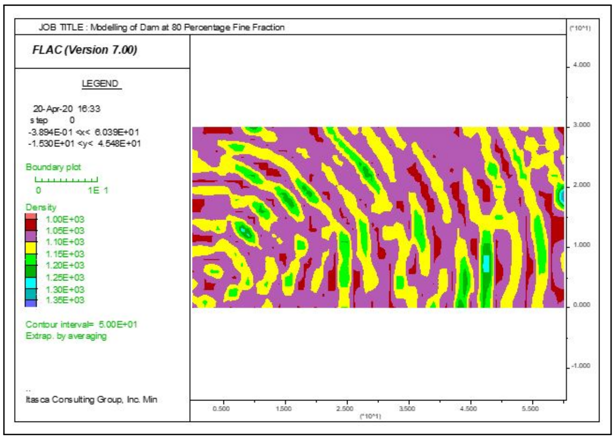

Figure 7: Density of Foundation Material at 80 percentage Fine Fraction.

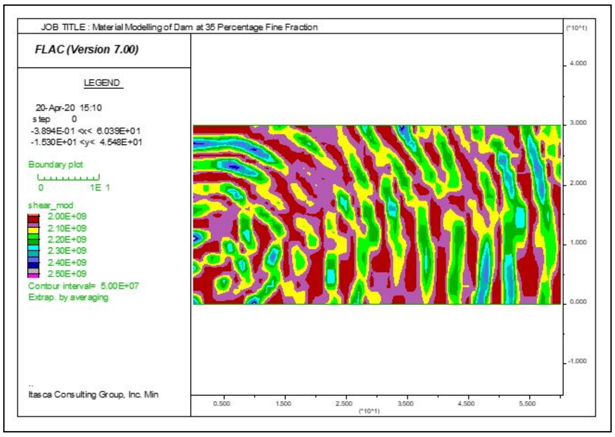

Figure 8: Shear Modulus of Foundation Material at 35 percentage Fine Fraction.

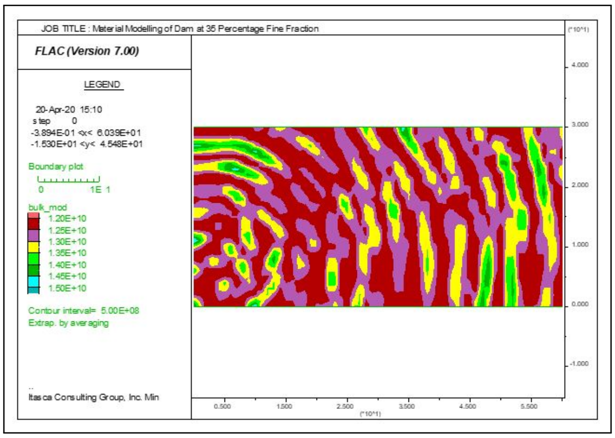

Figure 9: Bulk Modulus of Foundation Material at 35 percentage Fine Fraction.

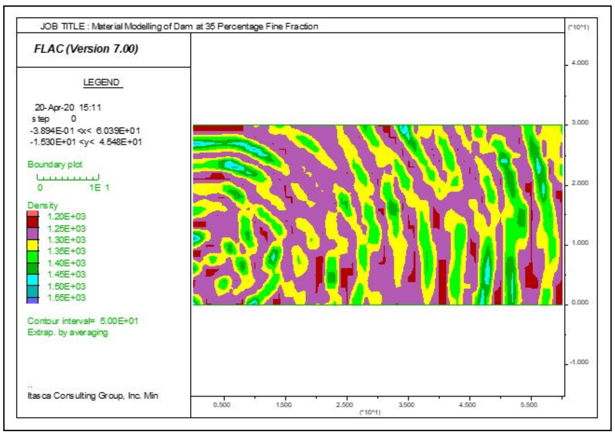

Figure 10: Density of Foundation Material at 35 percentage Fine Fraction.

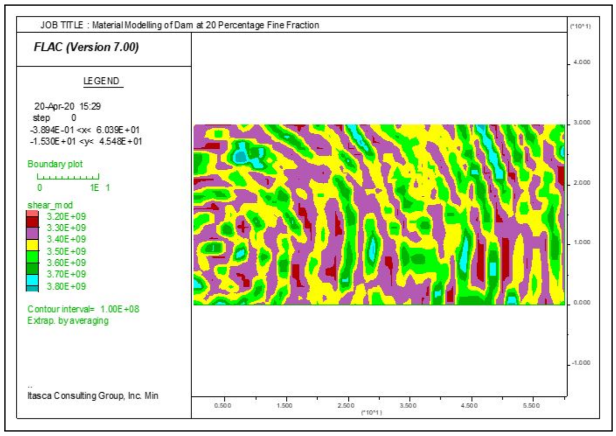

Figure 11: Shear Modulus of Foundation Material at 20 percentage Fine Fraction.

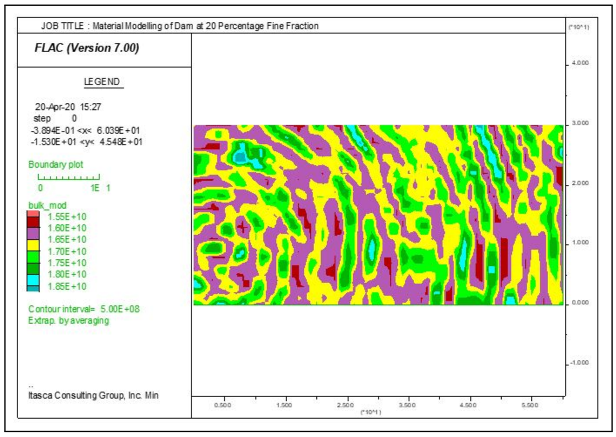

Figure 12: Bulk Modulus of Foundation Material at 20 percentage Fine Fraction.

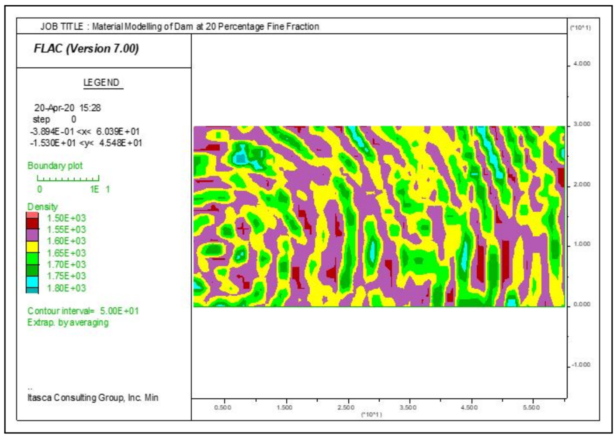

Figure 13: Density of Foundation Material at 20 percentage Fine Fraction.

The total height and base width of gravity dam are 27m and 20m as shown in below figure:14. The sum of vertical and horizontal forces are found to be 4218.05KN and 1883.52 KN. The resisting and overturning moment are calculated 75562.94 KNm and 35333.78KNm. Total stress on toe and heel are 240640 N/m^2 and 181166 N/m^2. The eccentricity of dam is found to be 0.47. The factor of safety against overturning and sliding are estimated more than 2 and 1.5. Thus, the stability of dam is assured from perspective of sliding and overturning. Now, it needs to be assured on bearing capacity for its stability.

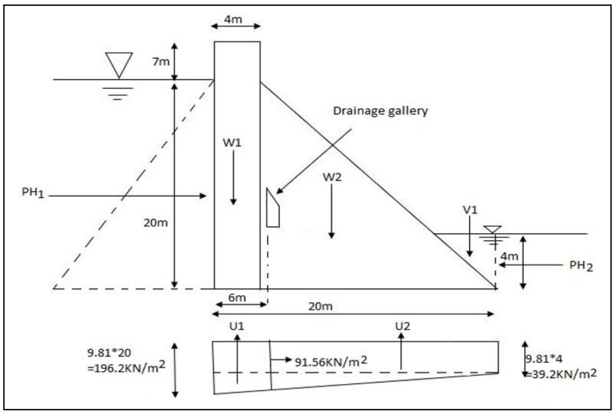

Figure 14: Gravity Dam.

4. Modeling Process

Secant pile techniques with combination of compaction and consolidation grouting increases the bearing capacity of dam foundation. Grouting helps to enhance the bearing capacity of weak deposits and consequently decrease the degree of settlement. At first, secant pile boundary is constructed on outer periphery to enclose the targeted area. It is necessary to ensure boundary doesn't deform during different combination of grouting.

The assumption is that, with the help of consolidation or compaction grouting the voids will be filled by cemented material such that the fine fraction will be decreased and consequently the stiffness/ density of the material will be increased. This is represented by the increase in K and G values.

In a mixture of alluvial deposits containing boulders, gravels, silt and sand, boulder has excessively higher stiffness comparing to others four. Then, gravel has higher stiffness and the other two has relatively low stiffness. The bearing capacity of alluvial deposits depends upon the overall stiffness of the deposits. There is a high chance of excessive deformation if the fraction of boulder is relatively low comparing to others. To increasing the bearing capacity of deposits, it is necessary to increase the stiffness of fine fraction in alluvial deposits. This is achieved by performing consolidation and compaction grouting with enough pressure. Grouting consolidate the fine fraction in deposits and decreases the volume of fine content. When we make the finer particles stiffness close to the boulder stiffness at that condition, we can be assured that there won't be deformation. Since stiffness of boulder is more than rock.

To study the effect of percentage fine fraction on the stability of Rolwaling Dam in alluvial deposits, a two-dimensional finite difference-based software is selected for modelling. The dam is modelled in plane-strain condition. The material modelling is done through Mohr-Coulomb material model. Soil-Gravel: mixture of gravel and sand is chosen. The dam body is modelled at natural condition of Rolwaling Khola considering linear variation of material upto 30m depth. The uniformly varying load (trapezoidal) is put in model considering full reservoir condition. The foundation material is considered as completely saturated. The dam is analysed considering linear distribution of foundation material. The material modeling of heterogeneous material is done considering random distribution of 80,35 and 20 percentage fine fraction. This decrease in percentage fine fraction is attained in field by combination of consolidation and compaction grouting, and deep mixing. This is checked in field by drilling core.

The different modeling case of gravity dam done are as follows:

1. Linear Distribution of homogeneous Materials
(a) Linear distribution of homogeneous material at 80, 60 and 40 percentage fine fraction

(b) Linear distribution of homogeneous material at 50, 40 and 35 percentage fine fraction

(c) Linear distribution of homogeneous material at 30, 25 and 20 percentage fine fraction

(d) Linear distribution of homogeneous material at 20 percentage fine fraction

2. heterogeneous random distribution of Material
(a) Random Distribution of heterogeneous Material at 35 percentage Fine Fraction

(b) Random Distribution of Heterogenus Material at 20 percentage Fine fraction

5. Results and Discussion

The following are the results which shows deformation, vertical stresses, deformation histories at different points on two cases: Linear distribution of Material, heterogeneous distribution of material. The first case is linear distribution of homogeneous material of Rolwaling khola at Natural Conditions (figure:15 to figure:27) and the second case is random distribution of heterogeneous material at different percentage fine fractions (figure:28 to figure:33).

Figure 12 to Figure 15 shows the modeling of dam at natural conditions. At natural conditions there is 10m thickness of 80 percentage fine fraction at top, then 60 percentage fine fraction at middle and 40 percentage fine fraction at bottom. It shows the vertical displacement histories at 8 different points, vertical stress contours, and displacement of dams. The maximum displacement is found to be 1m at top layers below the toe of dam. The maximum vertical displacement contours at top of the foundation is 25mm. Since the stress on toe is more than stress on heel, maximum displacement on toe. The displacement histories plot at 8 different points below toe of dam shows the maximum deformation occurs at top portion of foundation which is more than 1m. Due to this dam completely collapses in bearing capacity. The vertical stress diagram shows that maximum vertical stress at natural conditions is about 3 X 10^5 N/m^2. The vertical stress distribution decreases with respect to depth. This is due to the load of dam. If there was no structure or load at the top, then the vertical stress distribution would increase with respect to depth.

In second case, the dam is modelled as homogeneous material consisting of 50,40, and 35 percentage fines fraction at top, middle and bottom of each layer 10m thick. The decrease in fine fraction is achieved through combination of consolidation and compaction grouting. The output of numerical modeling is shown in figure 19 to figure 21. The vertical stress diagrams show that maximum vertical stress at is about 3 X 10^5 N/m^2. The maximum vertical displacement at top of the foundation is found to be 450mm. The displacement contours are found of 10mm. There is slightly decrease in vertical stress distribution.

In third case, voids are filled up with cementing material through combination of compaction and consolidation grouting and when the percentage boulder fraction is 70 at top, 75 at middle and 80 at bottom i.e. 30,25, and 20 percentage fine fraction is at top bottom and middle. The decrease in fine fraction consequently, increase the stiffness of the deposits. This is represented in model through increase value in K, G and ρ. This is illustrated in figure 22 to figure 24. The maximum vertical displacement at top of the foundation is found to be 300mm through displacement histories plot. This shows the decrease in percentage fine fraction through grouting. The displacement contour at top is found to be 7mm. But there is no significant change in vertical stress distribution than second case.

In fourth case, the dam is modelled for percentage fine fraction of 20. This is achieved when voids are filled up with Cementous material through consolidation and compaction grouting. This can be check in field through core drilling. The fine fractions changes into a boulder fraction through binding of Cementous material. The output of numerical modeling is shown in figure 24 to figure 27. The maximum vertical displacement occurs just below the toe of dam and is found to be 50mm by plotting displacement histories at eight different points. The displacement contours at top of the foundation is found to be 6mm. The maximum vertical stress is on the region where there occurs maximum dam pressure. The maximum stress occurs below toe of dam which is found to be 2.5 X 10^5 N/m^2.

Material modeling at heterogeneous random distribution is performed at 35 percentage fine fraction and 20 percentage fine fraction from figure 28 to figure 34. The maximum vertical deformation by plotting deformation histories at eight different points is found to be 9mm. The bearing capacity of material is found out to be higher in heterogeneous random distribution than homogeneous distribution of material. The maximum vertical deformation on dam at 35 percentage fine fraction is found to be 7mm whereas at 20 percentage fine fraction it is found to be 1mm. The maximum vertical stress is found just below toe of dam at 20 percentage heterogeneous distribution of fine fraction which is of value 6 X 10^5 N/m^2 and 3.5 X 10^5 N/m^2 at 35 percentage fine fraction. In both cases maximum deformation occurs of around 9mm.

In sum up, from above results it is found out that mechanical parameters have direct influence on the stability of gravity dam on weak foundation. The mechanical parameters of boulder mix soil is improved through combination of compaction and consolidation grouting. The model incorporates the combination of compaction and consolidation grouting in model through increase value of bulk modulus of elasticity, shear modulus of elasticity and density. The increase in mechanical parameters decreases the settlement problem in alluvial foundation through decrease in percentage fine fraction. These calculations provide one of the methodologies to analyse dam foundation in alluvial deposits through use of FDM software.

1. Linear Distribution of homogeneous Materials

(a) modeling of Dam at layer of 80, 60 and 40 Percentage Fine Fraction

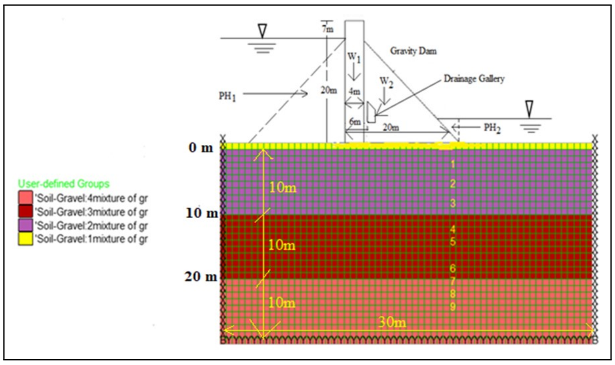

Figure 15: Model of Dam at layer of 80,60 and 40 Percentage Fine Fraction.

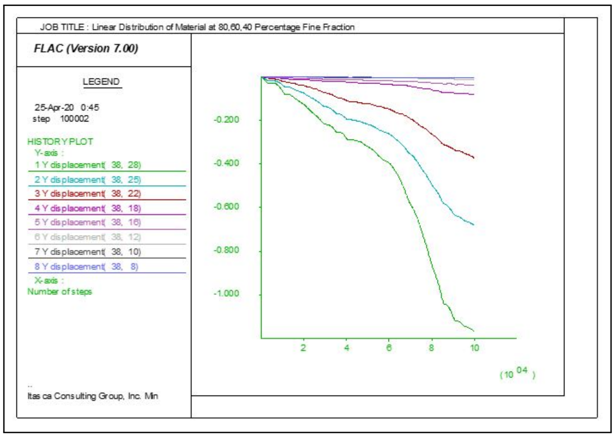

Figure 16: Deformation Histories of Dam at 8 different points.

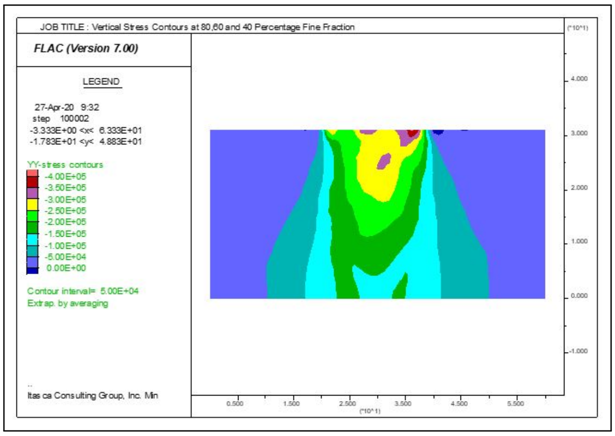

Figure 17: Vertical Stress Contours at layer of 80, 60 and 40 Percentage Fine Fraction.

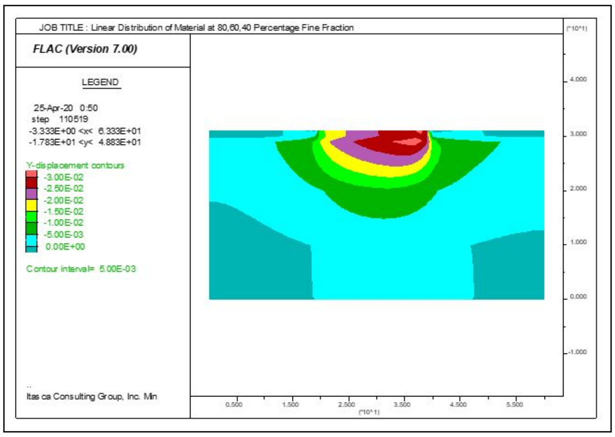

Figure 18: Displacement Contours of Dam at a layer of 80,60 and 40 Percentage Fine Fraction.

(b) modeling of Dam at layer of 50, 40 and 35 Percentage Fine Fraction

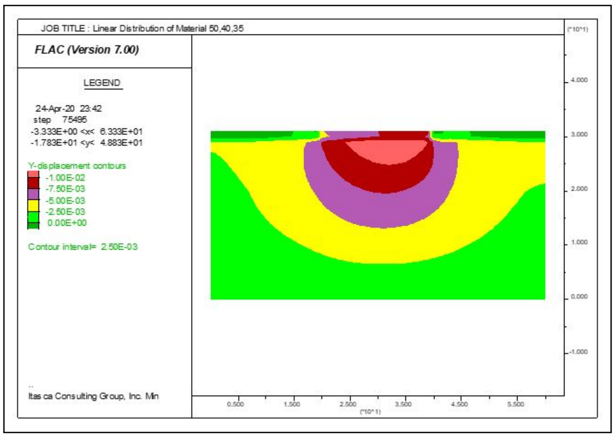

Figure 19: Vertical displacement contours at 50, 40 and 35 percentage fine fraction.

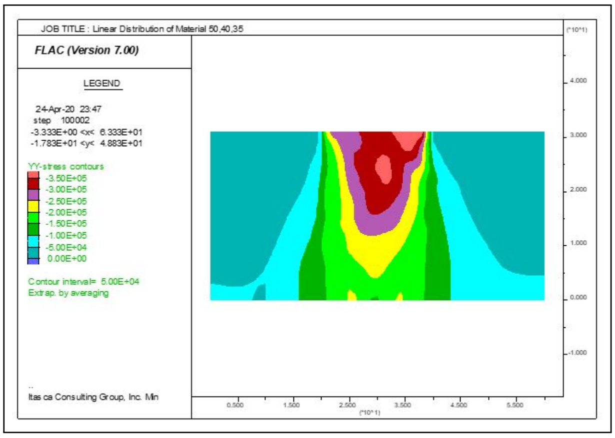

Figure 20: Vertical Stress contours at 50, 40 and 35 percentage fine fraction.

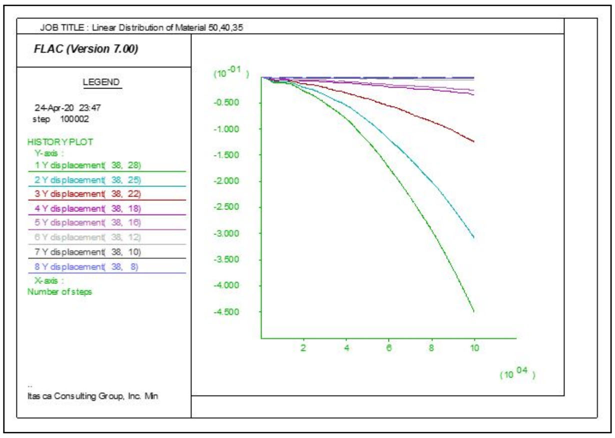

Figure 21: Vertical displacement histories at 8 different points.

(c) modeling of Dam at layer of 30, 25 and 20 Percentage Fine Fraction

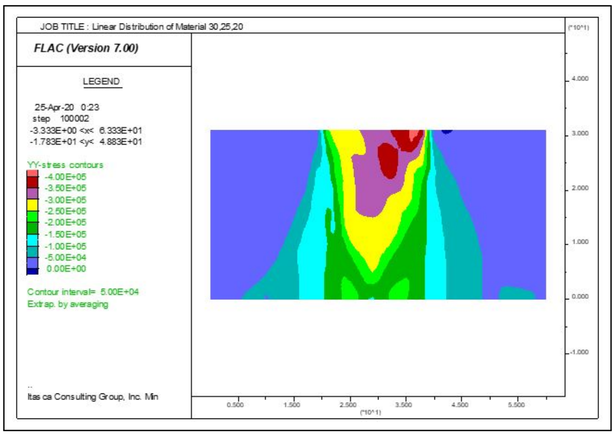

Figure 22: Vertical Stress Contours at 30, 25, and 20 Percentage Fine Fraction.

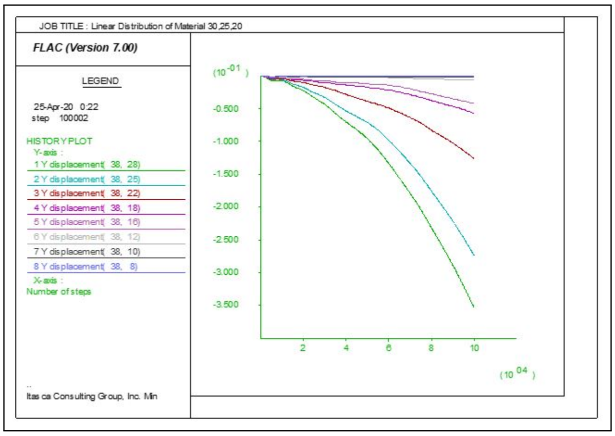

Figure 23: Vertical displacement Contours at 8 different points.

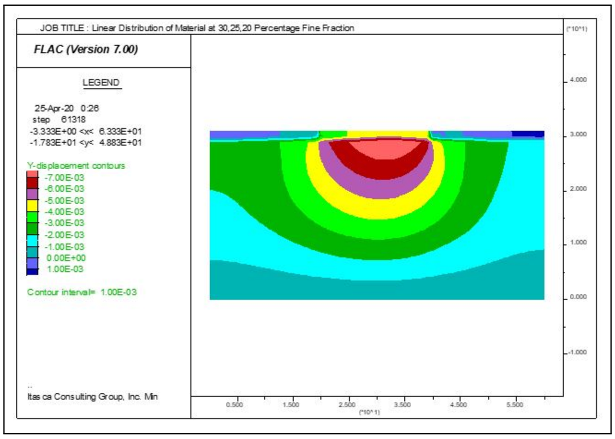

Figure 24: Vertical displacement contours at 30, 25 and 20 percentage fine fraction.

(d) modeling of Dam at layer at layer of 20 Percentage Fine Fraction

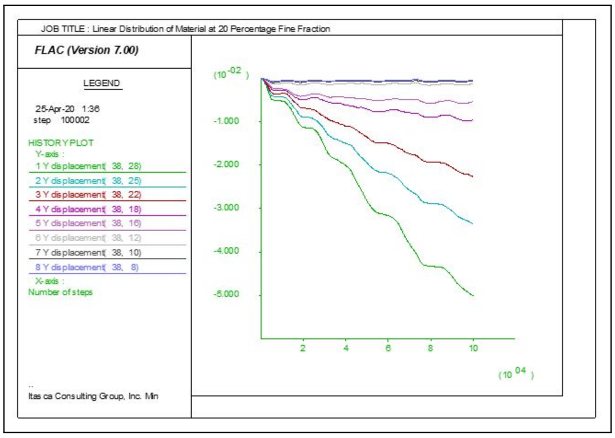

Figure 25: Displacement histories at 8 different points below toe of dam.

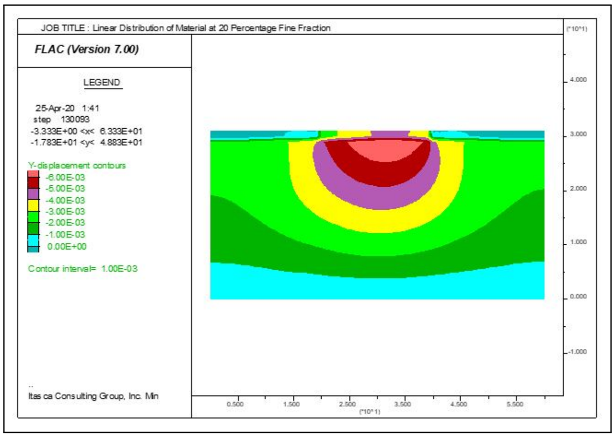

Figure 26: Vertical displacement of dam at 20 percentage fine fraction .

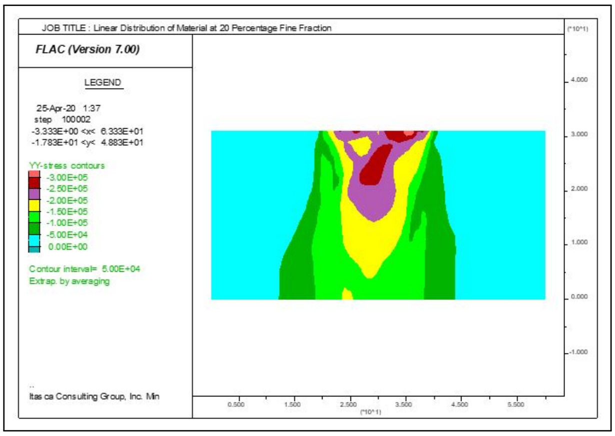

Figure 27: Vertical Stress Contours at 20 percentage fine fraction.

2. heterogeneous random distribution of Material
(a) heterogeneous random distribution of Material at 35 percentage Fine Fraction

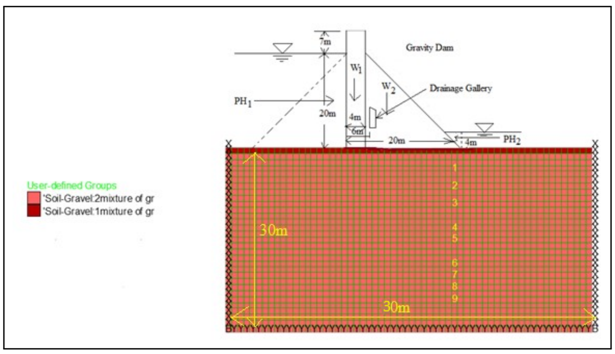

Figure 28: Modeling of Gravity dam at 35 Percentage fine fraction considering random heterogeneous distribution

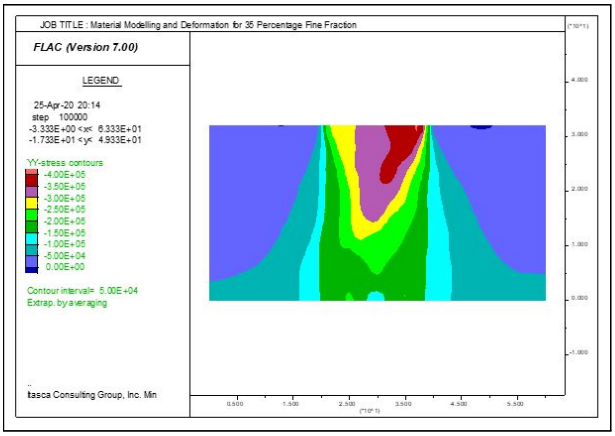

Figure 29: Vertical Stress Contours at 35 Percentage fine Fraction considering random heterogeneous distribution.

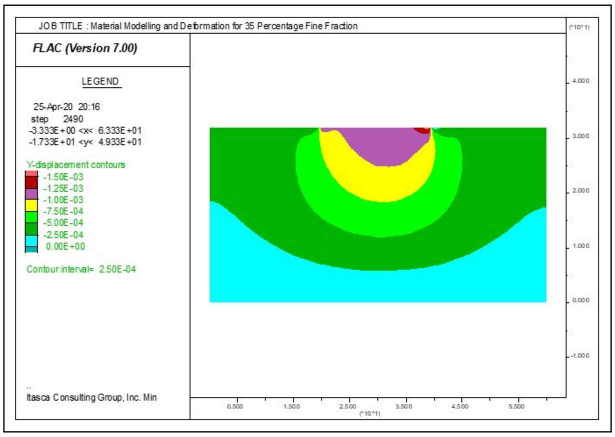

Figure 30: Vertical deformation of dam at 35 Percentage fine fraction considering random heterogeneous distribution.

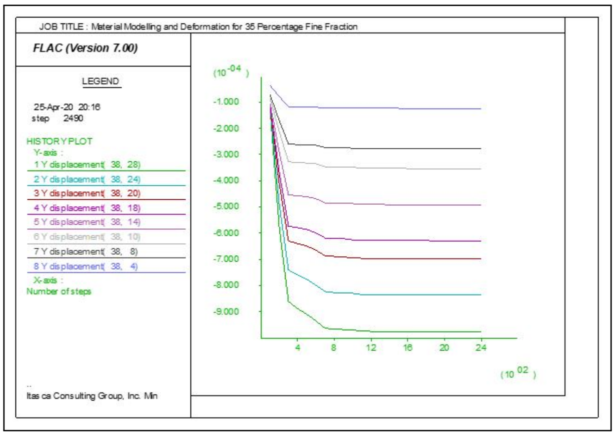

Figure 31: Vertical deformation histories of dam at 35 Percentage Fine fraction considering random heterogeneous distribution.

(b) heterogeneous random distribution of Material at

20 percentage Fine Fraction

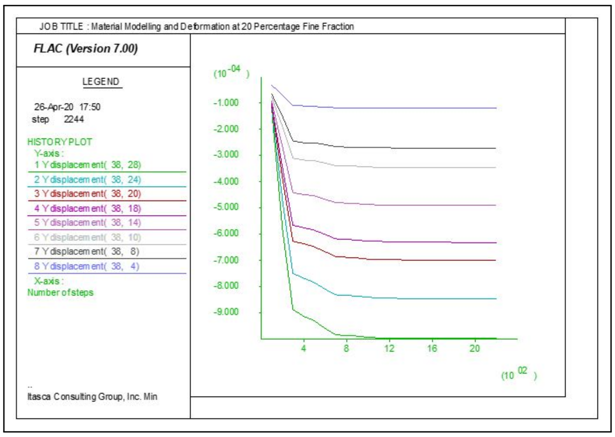

Figure 32: Deformation histories of dam at 8 different points considering random heterogeneous distribution.

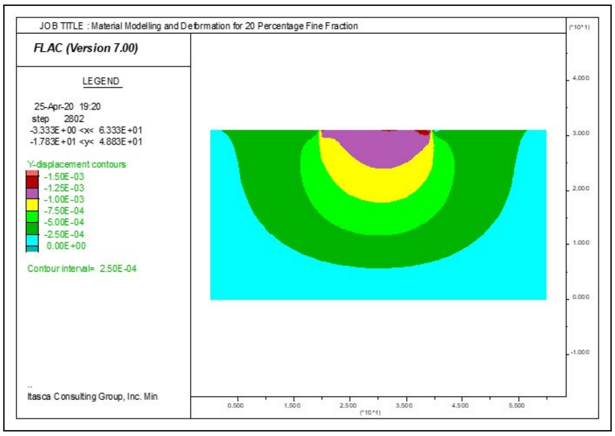

Figure 33: Vertical Displacement contours at 20 Percentage fine fractions considering random heterogeneous distribution.

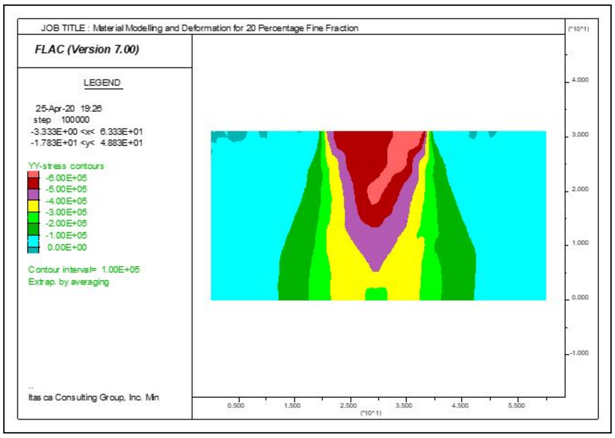

Figure 34: Vertical Stress contours at 20 Percentage fine fractions considering random heterogeneous distribution.

6. Conclusion

This study presented a methodology to analyse the stability of dam foundation in alluvial deposit in natural and improved soil strata by means of analytical and numerical method. First a relationship is established between percentage fine fraction with moduli of elasticity and density from the analysis of MASW survey data and borehole data on alluvial deposits. The relationship shows that mechanical properties of soil increase with decrease in percentage fine fraction. This relationship is used to find the mechanical properties of soil having different fine fractions of alluvial deposits. .The results are used to model the dam foundation in alluvial soil deposit. The model considered the reduction in the percentage fine fraction by the means of compaction and consolidation grouting, i.e., the cementation of fine material. The model simulated the process and the result obtained showed the decrease in deformation with the decrease in fine fraction. In total 6 numbers of models are analysed to represent the reduction in fine fraction from (0-75)%. The result from the numerical model representing (10-80)% reduction in fine fraction clearly depicts that the stability of dam in alluvial foundation can be achieved with the decrease in the fine fraction. For the 27m height gravity dam in assumed alluvial soil, the dam was stable after reduction in 75% of fine volume. The numerical model considered the homogeneous and random distribution of the fines and coarse material. The homogeneous material assumed uniform value of strength parameters K, G and ρ, i.e., average value of boulders and fines. The heterogeneous material model represented the random distribution of different fraction of boulders and fines and consequently the strength parameters. When an equal stress is applied at linear homogeneous material model and random heterogeneous material model. The bearing capacity of heterogeneous material model is found higher than homogeneous material model at equivalent percentage fine fraction. The vertical stress on alluvial deposits is found higher in case of heterogeneous material distribution than homogeneous material distribution at equivalent percentage fine fraction.

Moreover, the method presented to analyse the stability of dam foundation in alluvial foundation represented the load deformation mechanism in the foundation at the natural and improved soil. The numerical model result showed the validity of the method.

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