Granular columns in improving stability of vulnerable slopes - search for the optima by genetic algorithms

Les colonnes granulaires en améliorant la stabilité des pentes vulnérables – la recherché des optimums par des algorithmes génétique

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ABSTRACT
A mathematical model of a unit cell of a 'granular-pinned' slope had been analyzed (Saha 2001) to predict the increased resistance of potential sliding mass of the 'pinned' slope due to higher shear strength and free-draining characteristics of the 'granular-pin' or column. The present investigation illustrates the effectiveness of a new generation optimization procedure, the genetic algorithms (GA), to find out the minimum Factor of Safety of virgin slope vis-à-vis reinforced slope. GA does not require problem specific knowledge for carrying out the search since it is a tool guided by stochastic principles instead of gradients. The objective function to be optimized in the two cases has been taken as the factor of safety expression of Bishop's simplified method (1960) for virgin slope and Saha's (2001) expression for reinforced slope. A specific stretch of vulnerable 'Bhagirathi-Hooghly' river bank (-the southern part of River ***Ganges***- the major hydrodynamic system that formed the world's largest delta) has been chosen for the analysis. The study compares the results of prediction of failure susceptibility of river bank by directed grid-search in literature (Parua, 1992) with the present random search analysis. It emerged from the study that marked improvement in stability of such slopes could be achieved by granular-pinning that results in changing the potential virgin failure surface. Both gradual drawdown (GD) and instantaneous drawdown (ID) analysis exhibited marked improvement; though improvement in ID case, that is likely to govern in tidal deltaic zones, is about thrice than that obtained in GD case.

RÉSUMÉ
Un modèle mathématique d'une cellule d'une pente (considéré une composition des épingles granulaires, comme colonne) a été analyse (Saha, 2001) pour prévoir de l'augmentation de la résistance de la masse potentielle de la pente (des épingles) a glisser a cause des caractéristiques de la plus force en tente et l'augmentation de la capacité à drainer des épingles granulaires. La recherche actuelle illustre la' efficacité d'un procède de genre nouveau- l'algorithme génétiques (GA), pour trouver le Facteur de Sécurité minimum pour la pente vierge et aussi pour la pente armée. L'algorithme génétique na pas besoin de la connaissance spécifique d'un problème pour exécuter la quête parce que c'est un outil guide par principes stochastiques au lieu de pente. L'Object est pour optimiser du facteur de la sécurité en deux cas, la méthode simplifiée de Bishop (1960) pour la pente vierge. et la méthode de Saha (2001) pour la pente armée. Une région de la rive vulnérable de 'Bhagirathi-Hooghly' (- la partie du sud du fleuve ***'Ganges'*** ou formé le plus grand delta de la monde par le système-majore del'hydrodynamique) a été choisi pour analyser. C'étude compare les résultats de la prédiction de susceptibilité d'échec de la rive de fleuve par la méthode normale – 'directed grid search'- (á faire les grilles et chercher systématiquement) dans la littérature (Parua 1922) avec l'analyse présente de quête â Aventure. Il a émerge d'étude que on peut atteindre une amélioration notable en stabilité des pentes par considération des épingles granulaires, qui change la potentiel surface vierge en panne. Toutes deux analyses de l'abaissement du niveau d'eau en situations – graduel et instantané ont montré l'amélioration notable; mais l'amélioration dans le cas l'abaissement instantané qui existe en zones deltaïques da marée, est à peu prés trois fois que cela obtenue en cas de l'abaissement graduel.

Keywords : genetic algorithms, slope stability, stone columns, optimization technique, random search

1 INTRODUCTION

"GA" is a little applet that demonstrates the genetic algorithm and has sucessfully been applied to solve a wide variety of optimization problems such as scheduling, computer games, stock market trading, medical, adaptive control, transportation and the travelling salesmen problem. GA could be combined with the **basic thrust of Artificial Intelligence (AI)**, which is to get computers to produce automated refined and superfast outputs.

The procedure is based on the mechanics of natural selection and evolution that **mimics the principles of natural genetics and survival of the fittest rule**. Here, one has the liberty to start with a very wide range of values (a 'population' of points) for the decision variables and process the value convergence of the objective function to near optimal solution at a rapid rate which is independent of the initial vector. **GA work with string-coding of variables instead of the variables** and the advantage of working with coding of variables is that the coding discretizes the search space, even though the function may be continuous. Moreover, since GAs require only function values at various discrete points, "a discrete or discontinuous function may be handled at no extra cost"! (Deb, 2000). Since this algorithm is an abstraction from a natural phenomenon, GAs are fundamentally different than classical and traditional optimization algorithms. They are computationally simple but powerful in their search for improvement. Calculus-based search algorithms use derivative information to carry out a search while GA's work on binary-coded finite length strings containing 0's and 1's, and process a number of designs stochastically at a given time.

The program starts with a randomly generated finite size population of the 'n' coded decision variables (tri-variables in slope-stability context:- the abscissa (CX) and ordinate (CY) of the slip circle centre and the depth factor (N_d) of critical slip surface) within a very wide feasible search space. These coded design variables are 'artificial chromosomes' (and is a concatenation of binary sub-strings), where every character present is an 'artificial gene'. The 'fitness' of each chromosome is worked out and random pairs of reproduced above average parent chromosomes are crossed over probabilistically in a mating pool at some randomly chosen site to hopefully produce

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better offsprings. These child chromosomes are further mutated, again probabilistically at each locus to place the better child sub-strings in a new population set. The generated population set replaces the initial one and the loop continues with the aim to thrust each generated chromosome towards the global optima.

The stability analysis of a river bank, both virgin and reinforced, are carried out on the computer integrating GA with Bishop's simplified method for virgin slope and Saha's (2001) factor of safety expression for reinforced slope. The robustness of GA guided by stochastic principles that hunts for the global optima much faster than the deterministic processes has been highlighted.

2 PROBLEM DEFINITION & METHOD OF ANALYSIS

A real life problem of a specific stretch of vulnerable 'Bhagirathi-Hooghly' river bank has been analyzed for slope reinforcement with stone columns. This 'Bhagirathi-Hooghly' river is southern part of River Ganges- the major hydrodynamic system that formed the world's largest delta that occupies a major portion of Bangladesh and a greater part of West Bengal in India. In the long history of development of the Ganges Delta, the river shifted southeast and has reached its present position in the Bengal lowlands. Studies have shown that the exposed banks after erosion has revealed that in many reaches, "*a relatively thin topsoil overlays the typical fine sand layers in the Gangetic region, indicating that the river bank material is relatively more prone to the erosion action of the river and, possibly, the land was sometime in the past the playground of the Ganga*".

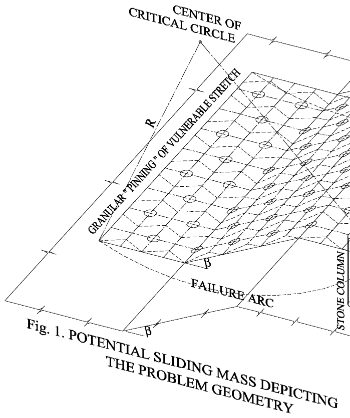


Fig.1. Potential sliding mass reinforced by stone columns

In the analysis it is considered that the granular-pins are installed in a regular array of triangular, square or hexagonal grid in plan area over the vulnerable stretch of the slope (Fig.1). The method of analysis is exactly in the same manner as for a normal slope stability problem except that each slice is considered of finite width equal to the effective diameter (D_e) of the unit-cell encapsulating the pin or column (of diameter d) and each row of granular column is converted into an equivalent, continuous strip or wall. In the analysis it is assumed that the length of this vulnerable stretch of reinforced slope is much greater than the failure width so that the complex three-dimensional problem may reasonably be simplified into a two-dimensional one. The unit-cell width of each slice is equal to the effective diameter (D_e) of equivalent circular area (A_r) for the chosen grid geometry and spacing (S). The row of column is assumed to be an equivalent, continuous strip of stonewall (Fig.2). The free body diagram of unit-cell (Fig.3) defines the problem. The area-ratio (A_r), spacing ratio (S_r), weighted average shear force mobilized along base of unit-cell $(\overline{S})$, weighted normal force (P_e), soil-stone column boundary strain compatibility, composite or equivalent parameters have been detailed elsewhere (Saha, 2001; Saha, 2003b). The feasible search-space delineation along-with composite soil properties are shown in Fig.4.

The critical failure surface is searched by application of GA (Saha, 2003a; Saha, 2003b, Saha, 2007) assuming the slope-stability problem as a bi-variable one (CX, CY). A recent study (Saha, 2008) assumes the same as a tri-variable problem (CX, CY and N_d). The random radius (R) is a function of the independent random variables-the abscissa and ordinate of circle centre (CX, CY) and depth factor (N_d), and the independent variables, width and height of slope (B & H). The randomly generated size of finite population (coded decision variables) is adopted as 64. 10-bit binary coding is chosen to represent variables CX, CY & N_d to get specific solution accuracy. Hence, the total chromosome length becomes 3x10=30. These 10-bits (or artificial genes) of 0 and 1 are generated randomly. The concatenated version of these 'genes' (substrings) forms the initial random population. Step by step simulation of the evolutionary process imitating natural genetics, several facets of the genetic process have been discussed elsewhere (Saha, 2008).

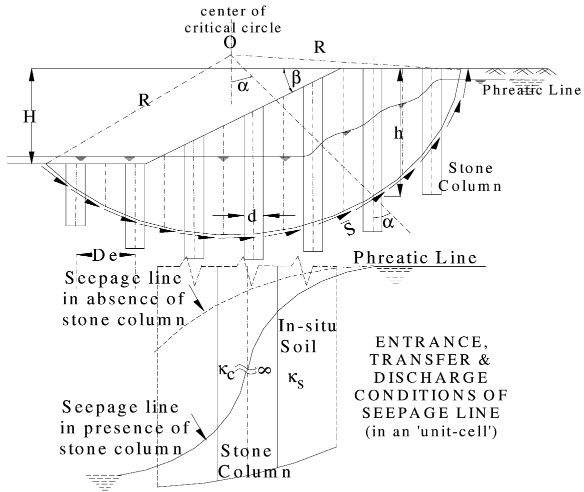


Fig.2. The Problem definition in a 2-D Plane

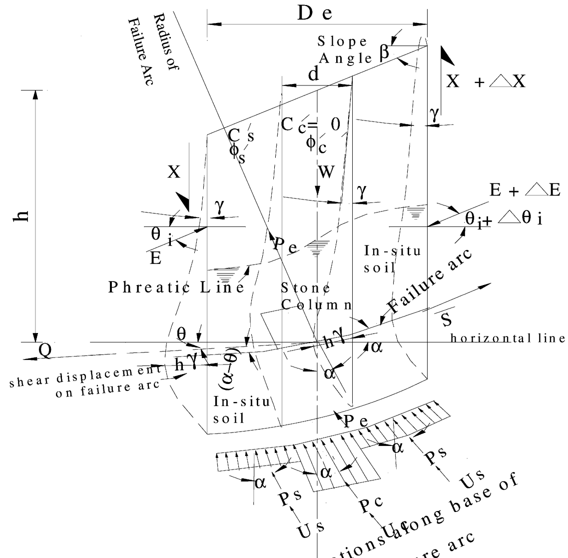


Fig.3. Free –Body diagram of Unit-Cell

3 OBJECTIVE FUNCTION-THE COMPOSITE FACTOR OF SAFETY OF REINFORCED SLOPE

The Factor of Safety (F_e) of reinforced slope is given by the expression (Saha 2001):

$$F_e = \frac{\displaystyle\sum_{Cell=1}^{No.ofCells} \frac{\left\{\left(1-\sqrt{A_r}\right)^2\left(\frac{c_s{}'}{\gamma_e H}\right)\left(\frac{D_e}{H}\right)+\left(\frac{D_e}{H}\right)\left(\frac{h}{H}\right)\left(1-r_{ue}\right)\tan\varphi_s{}'\right\}\sec\alpha}{F_e\left\{\dfrac{\left(1-\sqrt{A_r}\right)^2+mA_r\left(\dfrac{\tan\varphi_s{}'}{\tan\varphi_c{}'}\right)}{\left(1-\sqrt{A_r}\right)+m\sqrt{A_r}}\right\}+\tan\alpha\,\tan\varphi_s{}'}}{\displaystyle\sum_{Cell=1}^{No.of\ Cells}\left(\frac{D_e}{H}\right)\left(\frac{h}{H}\right)\sin\alpha}$$

where, $$m=\left(\frac{\cos2\beta+\sin2\beta\tan\varphi_s'}{\cos2\beta+\sin2\beta\tan\varphi_c'}\right)\left\{\frac{1+\tan2(\beta-\alpha)\tan\varphi_c'}{1+\tan2(\beta-\alpha)\tan\varphi_s'}\right\}$$

In the above expression the subscripts *s*, *c* and *e* stands for *soil*, *column* and *equivalent* parameters.

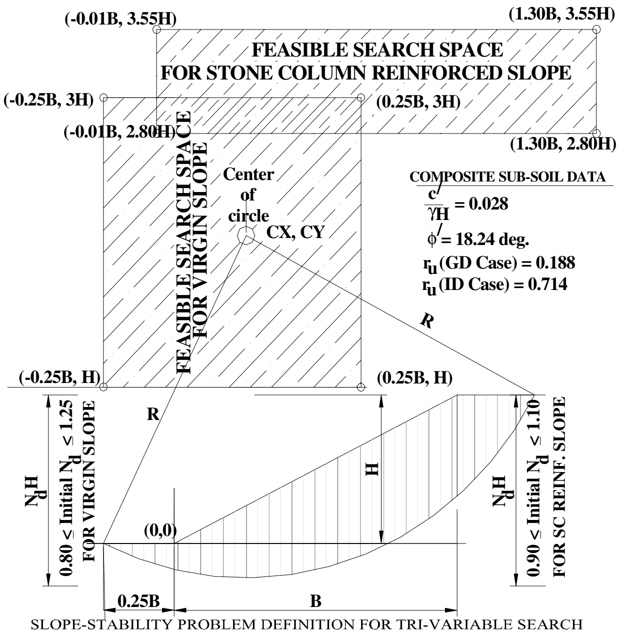
It may be noted that under limiting conditions, the above expression reduces to that of Bishop's simplified expression for FOS. The same is clarified below:

a. As $A_r \rightarrow 0$, $S_r \rightarrow \infty$, and the case resembles the normal condition of slope composed of in-situ soil only, i.e., $\varphi'_c=\varphi'_s=\varphi'$ implying m=1, & $\gamma_c=\gamma_s=\gamma$, $u_c=u_s=u$, so the equivalent subsoil properties reduce to those of the ambient subsoil and 'F_c' reduces to that of Bishop's equation for Factor of Safety.

b. As $A_r \rightarrow 1$, $S_r \rightarrow 1$, and the case resembles total replacement of the in-situ soil by granular backfill, wherein, $\varphi'_s=\varphi'_c$ again implying m=1, & $\gamma_s=\gamma_c$, $u_s=u_c$, and so the equivalent subsoil properties reduce to those of the granular backfill. Now, if for arguments sake, a negligibly small value of c'_c is assumed for the backfill, i.e. $c'_c\rightarrow 0$, but not = 0 then again 'F_c' reduces to that of Bishop's equation for Factor of Safety.

c. At limiting conditions, the local stiffness factor (or the ratio of mobilization potentials of soil and stone column) of individual slice (m_i) $\rightarrow 1$, as $A_r \rightarrow 0$ (no stone column) or, as $A_r \rightarrow 1$ (total granular backfill). Between these two extreme boundaries of A_r, m_i is a real number and a function of α_i, ϕ'_s & ϕ'_c for a given β .The sign of 'm_i' may be either positive or negative depending on β and α_i.

Further, the phreatic line droops down (Fig.2.) much faster upon column installation because of the free draining characteristics of the columns, thus reducing the hazards of failure under sudden drawdown condition.

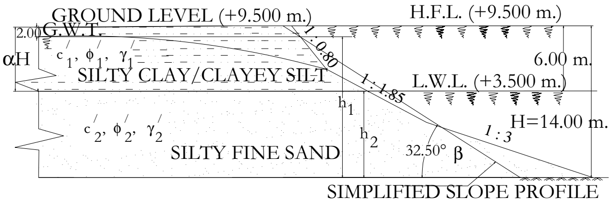


SLOPE-STABILITY PROBLEM DEFINITION FOR TRI-VARIABLE SEARCH

Fig.4. Slope, Soil Properties & Feasible Search Space delineation.

4 CHARACTERISTICS OF FAILURE STRETCH

This failure stretch is located about 230 km. from Bhagirathi offtake and about 2 km. upstream of the confluence point of River Jalangi. The tidal influence at this point is negligible. The site is located on the concave side of a meander loop and is subjected to severe erosion. The raw data and slope profile (Fig.5) are taken from Parua (1992) for further analysis and are reproduced below.



PROFILE OF R. BHAGIRATHI (GANGA)-MAYAPUR LEFT BANK
(Ref. Parua P.K., 1992)

Fig.5. Actual and simplified slope profile of Mayapur left bank (Ganga).

Weighted average values of soil parameters (Parua 1992) are considered in converting the bank with layered soil (upper silty clay layer underlain by silty sand) to a uniform soil for ease of calculation.

$$\alpha=\frac{\text{Thickness of upper clay layer}}{\text{Height of slope}},\quad c'=\alpha c_1{}'+(1-\alpha)c_2{}',$$

$$\phi'=\alpha\phi_1{}'+(1-\alpha)\phi_2{}',\quad \gamma'=\alpha\gamma_1{}'+(1-\alpha)\gamma_2{}'.$$

The design data as adopted by Parua (1992) are:

Slope angle (β)=	32.5^0	c_1'=	1.40 t/m^2
Height of slope (H)=	14m.	c_2'=	0.00 t/m^2
Base of slope (B)=	21.98m.	c'=	0.60 t/m^2
Ground water level (h_1)=	12.00m.	ϕ_1'=	0.00^0
Min. river water level (Max. Drawdown) (h_2)=	8.00m.	ϕ_2'=	32.01^0
Drawdown = h_m = h_1-h_2=	4.00m.	ϕ'=	18.24^0
α =	0.43	$\tan\phi_1'$=0.00	
$c'/\gamma H$ =	0.028	$\tan\phi_2'$=0.625	
r_u (ID)=	0.714	γ_1'=	1.44 t/m^3
r_u (GD)=	0.188	γ_2'=	1.60 t/m^3
		γ'=	1.53 t/m^3

Parua (1992) considered the upstream boundary of the flow domain as an equipotential surface, and assumed it to be at a distance of approximately $9h_m$ from the intersection point of maximum drawdown level and the slope. The bottom boundary was considered to be impervious, and taken at $3h_m$ below the drawdown level. It was inferred that the rate of flow in GD case is almost half that of ID case for a case. The permeability ratio between the upper clay layer to the lower sand layer was assumed as, k_{sand}/k_{clay}=1000.

Furthermore, it is stated that-"*ID represents a very transient phase, in which the free surface is at the GWL at high flood condition. This free surface is not a flow-line... The face of the slope, the free surface and the drawdown level acts as the top flow line... GD represents an equilibrium condition, in which the free surface is fully developed. The time required in arriving at this GD case, as computed by considering average rate of flow (81x10^{-3} m^3/hr.), worked out to be about 16 days, assuming that the GWL at some distance from the bank remains the same because of continued recharge*" (Parua 1992). This showed that in a tidal river, in which water level fluctuates twice in a day, ID case remains more relevant.

5 RESULTS & DISCUSSION

Fig.6 and Fig.7 depicts the critical circular failure (or slip) surfaces with their corresponding centers of rotation, as found out by Parua (1992), present GA analysis and by the MS-Excel

Solver Add-in, for the gradual (GD) and instantaneous (ID) drawdown cases respectively. It is revealed that the minimum FOS as found out by GA and Excel Solver are in close agreement to each other, though the GA search output is better than Excel Solver output for the ID case. It also transpired that minimum FOS as found by GA is about 38% less in the GD case, and 53% less in ID case, than that found out by directed grid search by Parua (1992). The nature of failure surfaces are also in agreement to above.

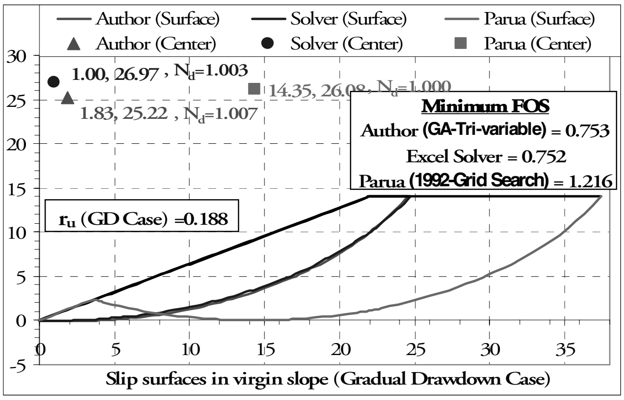


Fig.6. Comparison of FOS by diff. methods in virgin slope (GD Case).

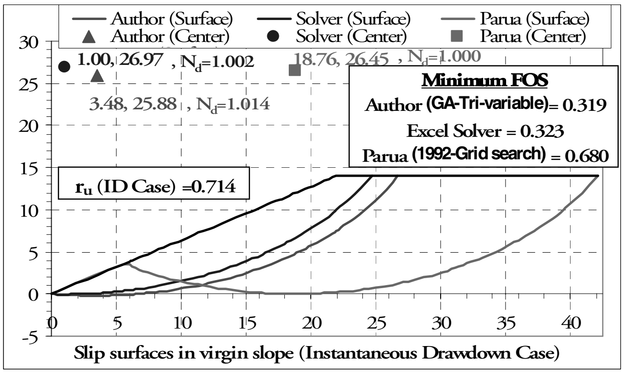


Fig.7. Comparison of FOS by diff. methods in virgin slope (ID Case).

Fig.8 and Fig.9 portrays the critical circular failure surfaces and their corresponding centers of rotation for the virgin and reinforced slopes by GA search method for the tri-variable problem.

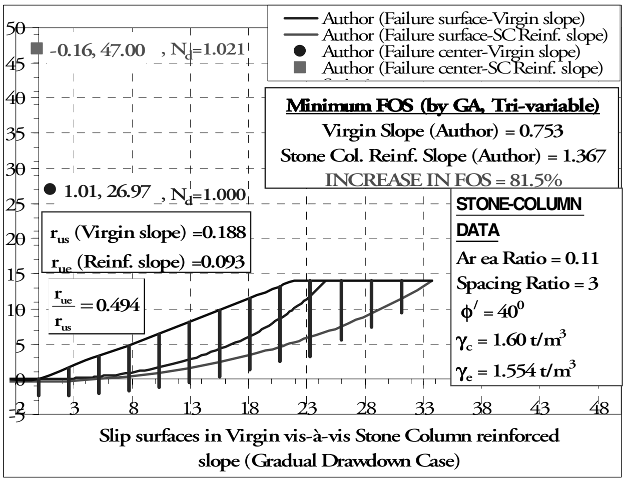


Fig.8. Comparison of FOS in virgin vis-a-vis reinf. slope (GD Case).

It emerged from the analysis that for a triangular arrangement of column geometry in plan area with a centre-to-centre spacing of thrice the column diameter (that is, for about 11% replacement of virgin soil by granular backfill), the equivalent pore-pressure ratio reduces by about 50% with simultaneous rapid pore-water-pressure dissipation due to free draining characteristics of the column and increased shear resistance of column backfill along failure surface, marked improvement in stability could be achieved. The minimum FOS as found out for reinforced slope is more than 1 for both GD and ID cases. It is about 82% more in the GD case, and 252% more in ID case, compared to that of virgin slope.

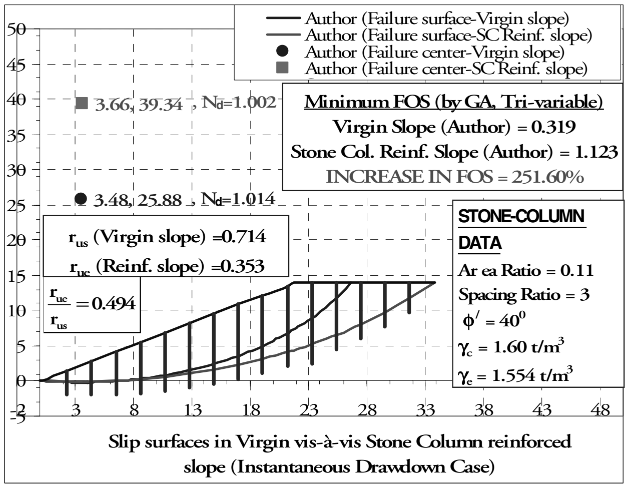


Fig.9. Comparison of FOS in virgin vis-a-vis reinf. slope (ID Case).

6 CONCLUSIONS

Reinforcement of natural vulnerable slopes by granular columns has been proposed for increasing its stability. Analysis has been made for both virgin slope to predict the susceptibility to failure and stone-column reinforced slope to arrest the same by increasing the factor of safety. Tools of analysis are genetic algorithm vis-à-vis other optimization techniques. The study unfolds that the GA generated critical failure arcs of a virgin slope become more flat near the toe with the shift of abscissa of the center of rotation towards the left than that obtained by a directed search, resulting in a lower FOS. In case of a reinforced slope, the center of rotation of GA failure arcs shifts higher up than the un-reinforced case, resulting in a much higher FOS. For the real life problem of a specific stretch of river 'Bhagirathi-Hooghly' (lower reach of river Ganges) investigated, it is found that marked improvement in stability could be achieved for reinforced slope for *gradual*, and more so for *instantaneous* drawdown conditions.

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