Behavior of Geogrid-Reinforced Sand Beds Analyzed through Multiple Regression

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Abstract - *Geogrid-reinforced soil foundations (GRSF) are widely employed in geotechnical engineering to enhance the bearing capacity of weak subgrades and to minimize footing settlement. Beyond their effectiveness in soft soil improvement, GRS systems contribute to the overall stability and durability of infrastructure by redistributing stresses and providing tensile resistance within the soil mass. These reinforcement techniques have proven valuable in applications ranging from highway embankments and bridge approaches to retaining structures and foundation systems, where both load-bearing efficiency and long-term serviceability are critical*

This study experimentally investigates the behavior of a square footing resting on unreinforced and geogrid-reinforced sand beds under static loading. Laboratory model tests were conducted using a rigid square footing of size 100 mm × 100 mm on sand prepared at a relative density of 35%. Commercially available biaxial polypropylene geogrids with a tensile strength of 40 kN/m were used as reinforcement. The depth of the first reinforcement layer was fixed at U/B = 0.3, while the reinforcement spacing (S/B = 0.3, 0.4 and 0.5) and number of layers (N=2,3,4&5) were varied. Results show significant improvement in bearing capacity and settlement response due to reinforcement. Regression models validated through ANOVA showed good agreement with experimental results, confirming the effectiveness of geogrid reinforcement under static loading.

***Key Words*: Shallow foundations, Geogrid-reinforcement, Bearing capacity, Static loading, ANOVA, Regression analysis, Square Footing**

1. INTRODUCTION

Geogrid-reinforced soil foundations (GRSFs) have been widely adopted in geotechnical engineering applications such as bridge abutments, approach slabs, building foundations, and embankments due to their effectiveness in improving the performance of shallow foundations. Soil reinforcement enhances bearing capacity and reduces settlement, offering an economical alternative to conventional ground improvement methods.

The geogrids are effective in reinforced foundation systems owing to their superior interlocking with granular soils. The performance of reinforced soil foundations is primarily governed by key geometric parameters such as the depth of the first reinforcement layer (U/B), the vertical spacing between reinforcement layers (S/B), and the number of reinforcement layers (N). These parameters significantly influence the load–settlement response and bearing capacity of reinforced soil foundations.

Numerous researchers **[1] to [21]** have carried out experimental investigations and analytical studies employing geosynthetic reinforcement materials to enhance the performance of soft soil foundations. Their work has demonstrated improvements in both foundation stability and structural integrity.

Abdrabbo et al. [2] experimentally demonstrated that soil reinforcement significantly improves the bearing capacity of sand, with greater improvement observed in loose sand. They reported optimum reinforcement parameters of L/B = 3.0 and d/B = 0.30, and observed a punching-shear type failure mechanism. **G. Madhavi Latha and Amit Somwanshi [11]** conducted laboratory model footing tests and numerical analyses on square footings resting on geosynthetic-reinforced sand beds to evaluate the performance of different reinforcement forms. Their results indicated that geocell reinforcement is the most effective in improving bearing capacity and stress–displacement behavior, while randomly distributed geogrid mesh elements are less efficient compared to planar and geocell reinforcements.

Asif Akbar et al.[4] studied the effectiveness of geocomposite reinforcement in layered soil systems as a sustainable solution for soft soils. They reported that geotextile–geogrid composite layers enhance soil confinement and shear strength, leading to 33.8–40.6 %

improvement in load carrying capacity along with reduced settlements. **Arvind Kumar and Swami Saran [4]** investigated the behavior of closely spaced strip and square footings on geogrid-reinforced sand and reported that providing continuous reinforcement layers significantly improves bearing capacity, settlement, and tilt, especially for closely spaced strip footings, while interference effects for square footings were minimal. **Bera et al.[5]** developed a power-based regression model to predict the bearing capacity of square footings on reinforced pond ash using extensive experimental data. Their analysis identified key reinforcement and geometric parameters influencing performance and achieved a high predictive accuracy (R^2_adj ≈ 0.945), with most predictions falling within acceptable error limits and validated using independent test data.

G. Madhavi Latha et al.[12] reviewed existing analytical approaches and developed a multiple regression equation to predict the ultimate bearing capacity of square footings on geosynthetic-reinforced sand considering key reinforcement and soil parameters. Their study showed that reinforcement aperture size plays a dominant role, and the proposed model reasonably predicts the bearing capacity of square footings on dense sand reinforced with planar geosynthetics.

Overall, the reviewed studies clearly indicate that soil reinforcement is an effective and reliable technique for enhancing the bearing capacity and deformation performance of foundation systems. The improvement is strongly influenced by reinforcement configuration, depth, spacing, stiffness, and soil density, with three-dimensional systems such as geocells and geocomposites showing superior performance due to enhanced confinement and interlocking. Continuous reinforcement layers are particularly beneficial in reducing settlement and tilt, especially for closely spaced footings.

In addition, regression-based predictive models have proven useful in capturing the complex interaction between soil and reinforcement, highlighting the potential for developing reliable design-oriented equations to estimate bearing capacity of reinforced soils under various loading and boundaryconditions.

1.1 Multiple Regression Analysis

Multiple Linear Regression (MLR) is employed in this study to quantify the relationship between response variables and multiple influencing parameters in reinforced soil systems. The method expresses the dependent variable as a linear combination of independent variables and regression coefficients, enabling assessment of both individual and combined parameter effects. Nonlinear behaviour is accommodated through polynomial and interaction terms, while model adequacy and predictive capability are evaluated using statistical measures such as R^2, adjusted R^2, and significance tests.

The selection of governing parameters for the regression analysis was based on their physical relevance and influence on the response of square footings resting on geogrid-reinforced sand beds under static loading. In the present study, bearing pressure and number of load cycles were considered as dependent variables, representing the load-carrying capacity and cyclic performance of the foundation system. Reinforcement spacing and number of geogrid layers were selected as independent variables, while relative density, reinforcement tensile strength, and U/B ratio were kept constant to isolate their effects. These parameters were chosen to capture the combined influence of reinforcement configuration on load–settlement behavior, bearing capacity, stiffness, and cyclic response, forming a consistent and reliable basis for regression modeling.

1.2 Regression Model

A regression model is used to describe and predict the relationship between a dependent variable and one or more independent variables based on experimental data. To account for nonlinear and interaction effects, a multiple polynomial regression model may be expressed as:

$$Y = \beta_0 + \Sigma\, \beta_i X_i + \Sigma\, \beta_{ii} X_i^2 + \Sigma\Sigma\, \beta_{ij} X_i X_j + \varepsilon$$

where Y is the dependent variable, X_i are the independent variables, β_0 is the intercept, β_i, β_{ii}, and β_{ij} are regression coefficients, and ε is the random error term. Such models provide a practical framework for interpreting experimental results and predicting system performance within the defined range of variables.

1.3 Significance Test for the Overall Regression Model

The overall significance of the regression model is examined to verify whether the set of independent variables collectively explains a statistically significant portion of the variation in the response variable. This evaluation is performed through hypothesis testing, where the null hypothesis assumes that all regression coefficients associated with the independent variables are equal to zero, indicating no linear relationship, while the alternative hypothesis implies that at least one coefficient is statistically significant.

$$H_0: \beta_1 = \beta_2 = \ldots = \beta_k = 0$$

$$H_1: \text{At least one } \beta_j \neq 0 \ (j = 1, 2, \ldots, k)$$

The adequacy of the model is assessed using the F-statistic, defined as the ratio of the mean square due to regression (MSR) to the mean square error (MSE):

$$F = MSR / MSE$$

Where

$$MSR = SSR / k$$

$$MSE = SSE / (n - k - 1)$$

Here, *k* denotes the number of independent variables and *n* represents the total number of observations. The regression sum of squares (SSR), error sum of squares (SSE), and total sum of squares (SST) are expressed as:

$$SST = \Sigma (y_i - \bar{y})^2$$
$$SSR = \Sigma (\hat{y}_i - \bar{y})^2$$
$$SSE = \Sigma (y_i - \hat{y}_i)^2$$

where y_i are the observed values, $\hat{y}_i$ are the predicted values from the regression model, and $\bar{y}$ is the mean of the dependent variable. These components satisfy the fundamental ANOVA relationship:

$SST = SSR + SSE$

Table -1: ANOVA Results for Regression Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-value
Regression	SSR	k	MSR = SSR / k	F = MSR / MSE
Error (Residual)	SSE	n − k − 1	MSE = SSE / (n − k − 1)	—
Total	SST	n − 1	—	—

A statistically significant regression model is identified when the calculated F-value exceeds the critical value at a chosen significance level, indicating that the model explains a substantial proportion of the observed variability compared to random error.

Where:

n = total number of observations
k = number of independent variables
SST = total sum of squares
SSR = sum of squares due to regression
SSE = sum of squares due to error

1.4 Goodness of Fit of the Regression Model

The goodness of fit of a regression model reflects its ability to represent experimental data and explain the variation in the dependent variable. This is commonly assessed using the coefficient of determination (R^2), which varies between 0 and 1, with higher values indicating improved model performance. However, since R^2 may artificially increase with the addition of extra variables, the adjusted coefficient of determination is adopted to account for the number of predictors in the model. The adjusted R^2 is expressed as:

$$\text{Adjusted } R^2 = 1 - [(1 - R^2)(n - 1)/(n - k - 1)]$$

where *n* is the total number of observations and *k* is the number of independent variables. A regression model exhibiting a high adjusted R^2, along with a low standard error and randomly distributed residuals, is considered statistically adequate for representing the experimental behaviour within the specified range of variables.

1.5 Significance Tests for Regression Coefficients

In multiple linear regression analysis, the statistical significance of individual regression coefficients is examined to evaluate the contribution of each independent variable while accounting for the effects of other predictors. For each regression coefficient βj, the following hypotheses are tested:

$$H_0: \beta j = 0$$
$$H_1: \beta j \neq 0$$

The significance of each coefficient is assessed using the t-statistic, expressed as:

$$tj = \hat{\beta} j / SE(\hat{\beta} j)$$

where $\hat{\beta}j$ is the estimated regression coefficient and $SE(\hat{\beta}j)$ is its standard error. A regression coefficient is considered statistically significant when the corresponding p-value is less than the selected significance level (α). The sign and magnitude of statistically significant coefficients indicate the direction and relative influence of the associated variables, enabling identification of the key parameters governing the regression model.

1.6 Variables Included in the Analysis and Selection Technique

Variables were selected based on physical relevance and their influence on reinforced sand behavior. The number of reinforcement layers (N) and reinforcement spacing ratio (S/B) were taken as independent variables, while relative density, depth of the upper reinforcement layer (U/B), and tensile strength were kept constant. Bearing pressure and number of load cycles were considered as dependent variables under static loading, respectively, ensuring a stable and reliable regression model.

2. REGRESSION ANALYSIS OF MODEL TESTS FOR STATIC LOADING

Multiple linear regression analysis was performed on the results of model footing tests conducted under static loading to establish a predictive relationship between bearing pressure and reinforcement configuration parameters. The regression analysis was carried out using the least-squares method with Analysis of Variance (ANOVA) to evaluate model adequacy. The reinforcement spacing ratio (S/B) and the number of reinforcement layers (N) were considered as independent variables, while bearing pressure (q) was taken as the response variable. Throughout the experimental program, the relative density of sand, tensile strength of reinforcement, and depth of the uppermost reinforcement layer (U/B) were maintained constant.

The proposed regression model for static loading is expressed as:

$$q = \beta_0 + \beta_1(S/B) + \beta_2 N + \beta_3 N^2 + \beta_4 N^3 + \beta_5(S/B)N$$

where β_0 represents the intercept and β_1 to β_5 are the regression coefficients. Higher-order polynomial terms of the number of layers and an interaction term between reinforcement spacing and number of layers were incorporated to account for nonlinear and combined effects. The regression model was developed using a total of twelve experimental data points.

2.1 Input Data for Regression Analysis

Based on the regression analysis of the experimental results, the final empirical expression for bearing pressure under static loading is given by:

$$q \;=\; -10226.07 + 1106\left(\frac{S}{B}\right) + 10747.57\,N - 2454.17\,N^2 - 1338.50\left(\frac{S}{B}\right)N + 196.33\,N^3$$

where
q = bearing pressure,
S/B = spacing ratio between reinforcement layers, and
N = number of reinforcement layers.

The above equation incorporates linear, nonlinear, and interaction terms to capture the combined influence of reinforcement spacing and number of layers on the bearing pressure of the reinforced sand bed within the investigated parameter range.

Table 2: Experimental data

S/B	N	N²	S/B × N	N³	Bearing pressure (kN/m²)
0.3	2	4	0.6	8	2552
0.3	3	9	0.9	27	4348
0.3	4	16	1.2	64	4843
0.3	5	25	1.5	125	5007
0.4	2	4	0.8	8	2358
0.4	3	9	1.2	27	4088
0.4	4	16	1.6	64	4357
0.4	5	25	2.0	125	4428
0.5	2	4	1.0	8	2274
0.5	3	9	1.5	27	3763
0.5	4	16	2.0	64	3891
0.5	5	25	2.5	125	3959

2.2 Results of Regression Analysis and Model Significance

The adequacy and statistical validity of the proposed regression model were evaluated using Analysis of Variance (ANOVA). The coefficient of determination obtained from the analysis (R^2 = 0.9986) indicates that 99.86 % of the total variation in bearing pressure is explained by the selected independent variables, demonstrating an excellent level of agreement between the experimental and predicted results. The very high F-value and extremely low p-value confirm that the regression model is statistically significant at conventional confidence levels and that the observed relationship between bearing pressure and reinforcement parameters is not due to random variation. The low residual error further indicates that the model reliably represents the experimental behavior within the investigated range of variables.

Table 3: ANOVA Results for Regression Analysis

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	Significance (p-value)
Regression	9,613,960.35	5	1,922,792.07	880.11	1.654×10^{-8}
Error (Residual)	13,108.32	6	2,184.72	—	—
Total	9,627,068.67	11	—	—	—

2.3 Goodness of Fit of the Model

The regression model exhibits an excellent fit, with Multiple R = 0.99932, R^2 = 0.99864, adjusted R^2 = 0.99750, and a low standard error of 46.74. These statistics confirm the strong agreement between experimental and predicted bearing pressure values and demonstrate the reliability of the model within the investigated range.

2.4 Significance Test for Individual Regression Coefficients

The statistical significance of individual regression coefficients was evaluated using *p*-values at a 95% confidence level ($\alpha = 0.05$) under static loading conditions. The results indicate that the number of reinforcement layers (N) has a significant influence on bearing pressure, while the higher-order terms (N^2 and N^3) confirm a pronounced nonlinear response. The interaction term $(S/B)\cdot N$ is also statistically significant, highlighting the combined effect of spacing and reinforcement layering, whereas the spacing ratio (S/B) alone is not significant within the investigated range. These findings demonstrate that bearing pressure is predominantly governed by reinforcement layering and its nonlinear and interaction effects, supporting the adopted regression formulation.

Table 4: Significance Test for Individual Regression Coefficients (Static Loading)

Source	Coefficient (β)	Standard Error	t-Statistic	p-value
Intercept	−10226.07	766.04	−13.35	1.09×10^{-5}
S/B	1106.00	543.08	2.04	0.0879

Source	Coefficient (β)	Standard Error	t-Statistic	p-value
N (Layers)	10747.57	706.90	15.20	5.11×10^{-6}
N^2	−2454.17	211.63	−11.60	2.47×10^{-5}
(S/B) × N	−1338.50	147.81	−9.06	0.000102
N^3	196.33	20.11	9.76	6.65×10^{-5}

2.5 Normality Check of Residuals

The normality of residuals was examined to verify the validity of the regression assumptions under static loading conditions. The Anderson–Darling test conducted at a significance level of $\alpha = 0.05$ yielded a test statistic of $A^2 = 0.354$, which is lower than the critical value of 0.679, indicating that the null hypothesis of normality cannot be rejected. In addition, the standardized residuals fall within acceptable limits without extreme outliers, confirming that the residuals are approximately normally distributed and that the regression model provides reliable statistical inference.

2.6 Comparison Between Experimental and Predicted Bearing Pressure

A comparison between experimental and predicted bearing pressure values was conducted to evaluate the predictive performance of the regression model under static loading conditions. As illustrated in **Fig 1**, the predicted values closely follow the reference line (y = x), indicating excellent agreement and high prediction accuracy. This is further supported by the high coefficient of determination (**$R^2 = 0.9986$**), while the small and randomly distributed residuals confirm the absence of systematic bias. Overall, the model reliably captures the influence of reinforcement spacing and number of layers on bearing pressure.

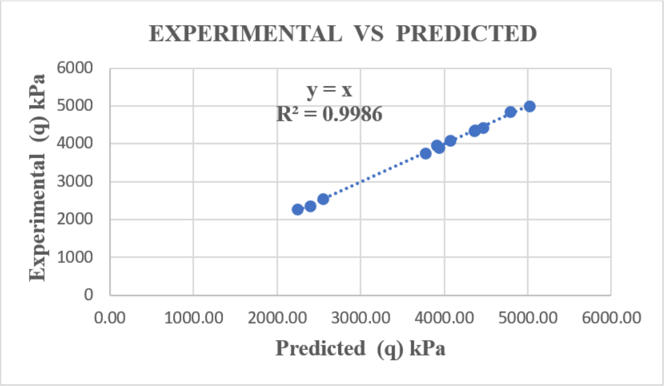

Fig -1: Comparison between Experimental and Predicted Bearing Pressure

2.7 Applicability and Limitations of the Regression Models

The proposed regression models reliably predict static bearing pressure and cyclic load response of reinforced sand foundations within the investigated experimental range of reinforcement spacing (S/B) and number of layers (N). The models are valid only within the tested parameter limits and should not be extrapolated. Although derived from laboratory-scale experiments, the models provide dependable predictions within their scope, while field application requires appropriate calibration.

3. CONCLUSIONS

A polynomial regression model was developed to predict bearing pressure (q) of square footings on geogrid-reinforced sand under static loading, with reinforcement spacing ratio (S/B) and number of reinforcement layers (N) as independent variables.

1. The model exhibited excellent predictive performance ($R^2 = 0.9986$, adjusted $R^2 = 0.9975$) with a low standard error (46.74), indicating strong agreement between experimental and predicted results.

2. Statistical validation using ANOVA confirmed the overall significance of the model, with reinforcement layering (N) identified as the dominant parameter influencing bearing pressure.

3. The significance of higher-order terms (N^2, N^3) and the interaction term (S/B·N) highlights the nonlinear and combined effects of reinforcement configuration.

4. Residual and normality analyses verified that regression assumptions are satisfied, with small, randomly distributed, and normally distributed residuals.

5. Although polynomial terms introduce multicollinearity, VIF analysis showed no adverse effect on predictive accuracy, as the model is intended for response prediction.

6. The proposed model is applicable within the investigated experimental range and provides a reliable tool for estimating static bearing performance of reinforced sand foundations, with field application requiring appropriate calibration.

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