Discussion on Consideration of Uplift Forces in Foundation Stability Checks

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Abstract: Foundation is probably the most important and critical component of any structure as overall stability of the superstructure depends on how robust the foundation system is. Numerous structural failures have taken place owing to inadequacy of foundation system adopted and these have often lead to huge losses of life and property. As such, foundation analysis should always be performed with due diligence towards adequate safety margins. However, at the same time, we cannot afford to overlook design optimization opportunities and provide overtly conservative foundation systems. The Engineer needs to formulate a reasonable tradeoff between design safety and design optimization.

Foundation failures may be either from loss of stability or structural failure to effectively transfer the superstructure loads to the ground. Stability failures can actually be pretty disastrous and are one of the most important considerations of foundation analysis, in which ratio of stabilizing forces to de-stabilizing forces are compared against allowable factor of safety.

This paper discusses two widely prevalent methods for analyzing overturning stability of foundations, sometimes referred to as Traditional overturning safety factor method and True safety factor method vis-à-vis their depiction of the actual stability scenario of foundation system and thereby recommends the most reasonable approach for different design conditions analyzed herein.

Keywords: Stability; Foundations; Overturning; Factor of Safety; Uplift.

Introduction

Stability of any structure depends primarily upon the stability of foundation system on which it rests. Due diligence must be exhibited while evaluating overall stability of the foundation system as any inadequacies may lead to catastrophic structural failures , causing huge losses of life and property. However, as professional engineers, we should also look for opportunities to add value by optimizing the design while maintaining its inherent safety.

Any foundation system experiences external forces in the form of Vertical downward forces, Uplift forces, Lateral forces and External Moments. Nature of these forces decides whether they shall have a stabilizing or de-stabilizing effect on the foundation system. Foundation system is designed such that effect of stabilizing forces is greater than de-stabilizing forces and the ratio is generally compared against a predefined value of Factor of safety (FOS). Beyond this FOS value, it can be deduced that the foundation system will be stable.

In stability analysis, overturning checks assume prime importance, in which ratio of stabilizing forces (moments) to de-stabilizing forces (moments) is compared against a Factor of Safety (FOS). Most codes and design practices recommend this FOS value to be greater than 1.5 in serviceability cases.

This paper discusses two widely prevalent methods for analyzing overturning stability of foundations, sometimes referred to as Traditional overturning safety factor method and True safety factor method vis-à-vis their depiction of the actual stability scenario of foundation system and thereby recommends the most reasonable approach for different design conditions analyzed herein.

Difference between these methods lies in the approach towards categorizing forces as being additive to the overturning moment or subtractive to the restoring moment.

Analysis Method -1

This method of analysis, sometimes referred to as Traditional overturning safety factor method, considers the overall net effect of vertical loads acting on the foundation. This means, any uplift load from superstructure shall be reducing the stabilizing effect of other vertical loads while downward vertical load from superstructure shall increase the stabilizing effect. In other words, uplift loads shall be reducing the net stabilizing effect on foundation, which shall be compared against overturning effect of lateral forces or moments. This method is widely adopted by Engineers throughout the world.

This method implicitly assumes that all vertical loads are stabilizing loads, capable of producing stabilizing moments only, while all lateral shear and moments shall act to de-stabilize the structure / foundation system.

Analysis Method -2

This method of analysis, which is sometimes referred to as True safety factor method, differs in its approach towards categorizing vertical loads for calculation of overall stability of foundation. It involves considering each and every component of load and thereby deciding whether it shall have stabilizing or de-stabilizing effect. Uplift forces are considered to be de-stabilizing and downward forces are considered to be stabilizing. All de-stabilizing forces are combined to calculate the overturning effect on the foundation while stabilizing forces are combined to calculate the net resisting effect to overturning.

This method of analysis becomes important for eccentric foundations where the vertical loads shall have different stabilizing and de-stabilizing effects depending on the direction of eccentricity.

Comparison between Method-1 & Method -2

It is interesting to note that above described two methods give a considerable variation in results for similar set of loading scenarios / conditions. There may exist a possibility that a foundation system found to be safe in one of the methods turns out to be unsafe in the other method. As such, an objective analysis and interpretation of the results from the two employed methods should help in judiciously selecting the approach to be applied to a particular design situation.

A sample comparative study is performed here for the above two methods for two distinct scenarios - a concentric and an eccentric foundation system, through manual calculations, with similar loading conditions. With varying horizontal loads, graphical results are presented to illustrate the differences in results.

Results

Consider a portal for preliminary analysis as shown in Fig. 1

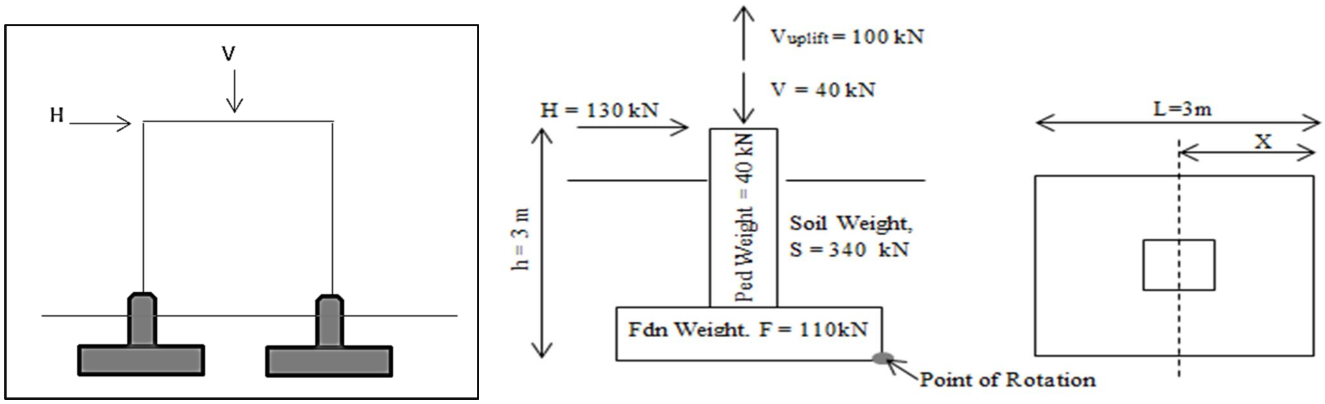

Fig. 1

Scenario 1 - Concentric Foundation

Method -1		
De-stabilizing Moments, Mo	H x h	= 130 x 3 = 390 kN-m
Stabilizing Moments, Ms	(V+P+F+S-V_{uplift}) x X	= (40+40+110+340-100) x 3/2= 645 kN-m
Overturning Ratio	Ms / Mo	= 645 / 390 = 1.65
Conclusion: Overturning Ratio i.e. 1.65 > Allowable FOS i.e. 1.5, Hence Foundation is Safe in Stability/Overturning.		

Method -2		
De-stabilizing Moments, Mo	(H x h) + (V_{uplift} x X)	= (130 x 3) + (100 x 3/2) = 540 kN-m
Stabilizing Moments, Ms	(V+P+F+S) x X	= (40+40+110+340) x 3/2 = 795 kN-m
Overturning Ratio	Ms / Mo	= 795 / 540 = 1.47
Conclusion: Overturning Ratio i.e. 1.47< Allowable FOS i.e. 1.5, Hence Foundation is Unsafe in Stability/Overturning.		

Fig. 2 shows results of two above described methods with variation in horizontal applied loads keeping remaining loads unchanged.

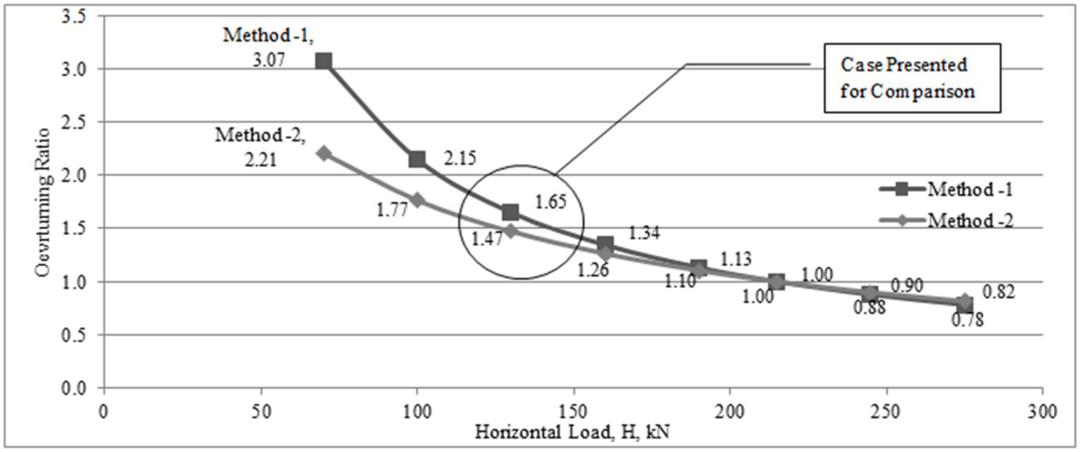

Fig. 2

Scenario 2 - Eccentric Foundation: (Eccentricity of 0.9m)

Method -1		
De-stabilizing Moments, Mo	H x h	= 130 x 3 = 390 kN-m
Stabilizing Moments, Ms	(V+P -V_{uplift}) x X + (F+S) x L/2	= (40+40-100) x (3/2-0.9) + (110+340) x 3/2 = 663 kN-m
Overturning Ratio	Ms / Mo	= 663 / 390 = 1.70
Conclusion: Overturning Ratio i.e. 1.70 > Allowable FOS i.e. 1.5, Hence Foundation is Safe in Stability/Overturning.		

Method -2		
De-stabilizing Moments, Mo	(H x h) + (V_{uplift} x X)	= (130 x 3) + (100 x (3/2-0.9)) = 450 kN-m
Stabilizing Moments, Ms	(V+P) x X + (F+S) x L/2	= (40+40) x (3/2-0.9) + (110+340) x 3/2 = 723 kN-m
Overturning Ratio	Ms / Mo	= 723 / 450 = 1.61
Conclusion: Overturning Ratio i.e. 1.61 > Allowable FOS i.e. 1.5, Hence Foundation is Safe in Stability/Overturning.		

Fig. 3 shows comparison of results for scenario 2

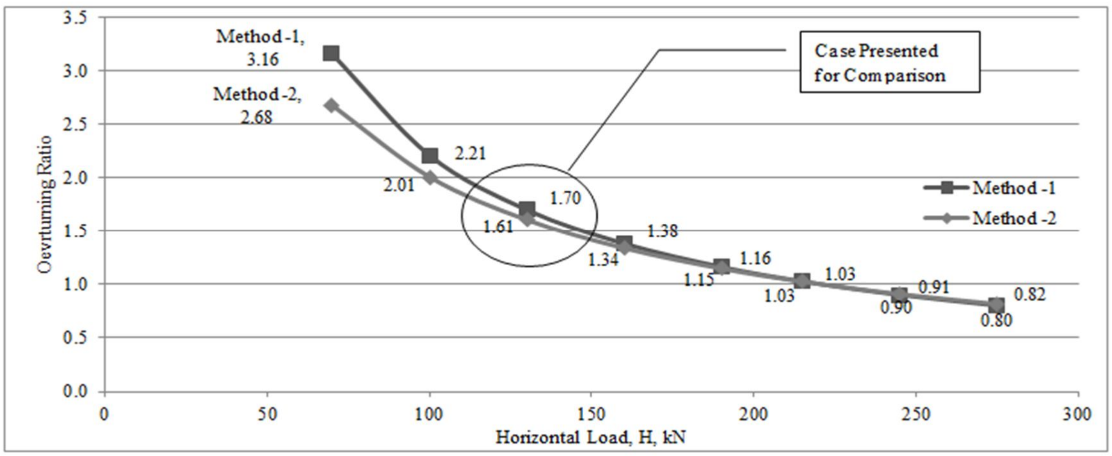

Fig. 3

It can be clearly inferred from the graph that results are varying considerably in these two methods for similar loading conditions for both Scenarios 1 & 2. In fact, for the given example in scenario 1, a foundation found to be adequate in Method-1, turns out to be unsafe in Method-2. In case of Scenario 2, it can also be seen that the results from the two methods appear to converge with increasing eccentricity towards the point of rotation.

Conclusion

It is now understood that the type of foundations system has a direct relation to the degree of variation in results from the two aforesaid methods. However, a cardinal question would be – "which of the two methods is more accurate/appropriate ?"

Let us consider a foundation with only vertical uplift loads from superstructure .If we go by the Method 2 (True safety factor method), we have an overturning moment from uplift loads and a restoring moment from soil/foundation weight. But, actually there cannot be any overturning unless the uplift load exceeds the restoring weight of foundation and soil. This essentially means that the end effect of uplift load from superstructure is to reduce the restoring effect of other vertical loads, which is the base assumption of our Method -1 (Traditional overturning safety factor method).

From the aforesaid example, we can probably safely conclude that Method 1 (Traditional method) should be appropriate for most foundation systems. Especially for isolated foundations, adoption of Method 2 will lead to exaggerated foundation size requirements, which may not be desirable for industrial projects, considering their cost and space constraints.

However, in case the engineer needs to build a design margin, especially for critical foundations with uncertainty of loading data, Method 2 may be adopted. Similar approach is employed by some available softwares like RISAFoot.

Having said this, the engineer needs to judiciously apply the recommendations herein to suit particular project requirements, with application of his/her engineering judgment based on past experiences.

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