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Owner Involvement - Choosing Risk Factors for Shallow Foundations

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Abstract: The engineer must always design to avoid injury and loss of life. However, other design decisions are purely economical. The owner should invest in the most economical foundation that will adequately support the building, considering both constructability and risk of failure. The owner chooses the site with its subsurface conditions, the structure and its foundation loads, and the available funding. The engineer must design a foundation that adequately supports the structure and balances the owner's cost with the performance of the foundation. Improved bearing capacity design methods have largely precluded stability failures, but excessive settlement remains problematic. The engineer measures the soil's deformation properties and predicts the amount of settlement that will occur. As some foundation movement will occur under any level of load, the engineer's design should allow a tolerable movement that also provides reasonable foundation cost. It may prove more cost effective to use smaller spread footings that settle a tolerable amount with a risk of minor repair rather than larger footings or deep foundations whose costs may overburden the construction budget. The authors present charts showing the probabilities of success of 90%, 95%, 99%, and 99.9% for limiting settlement plotted against its standard deviation. To increase the accuracy of the estimated settlement and the success probability, the settlement estimates are based on direct measurements of soil modulus using the Dilatometer. The charts are formatted for the owner to understand and to make the most appropriate choice for the building.

INTRODUCTION

Owners make many financial decisions on every project. They should choose the most economical foundation that will safely support their structure. Often, they choose a geotechnical engineer, who only performs a basic study for the project. This engineer typically does not measure the soil's deformation properties, but instead estimates those properties using crude correlations with as much as ±200% error. This study can be adequate if the subsurface conditions are very favorable and column loads are relatively light. For marginal subsurface conditions or heavy column loads, the geotechnical engineer often recommends overly conservative foundation designs that sometimes include unnecessary deep foundations. Instead of making poor recommendations, the geotechnical engineer should perform a more thorough subsurface investigation that measures the soils' deformation properties. Then the engineer can confidently calculate the settlement for each column and size the footings so that the structure will settle uniformly. Otherwise, the owner, often unknowingly, pays an excessive price for the poor design.

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SITE INVESTIGATION TO QUANTIFY RISK

The engineer needs reasonably accurate deformation tests to accurately predict settlement of shallow foundations. The oedometer test, standard penetration test (SPT), cone penetrometer test (CPT), pressuremeter test (PMT), and dilatometer test (DMT) are commonly used for shallow foundation design. The applicability of these tests to quantify the risk of undesirable settlement is discussed below.

Oedometer Test: Sampling, followed by consolidation testing in an oedometer in the lab, provides an accurate test of deformation properties. However, testing is time-consuming and is typically performed at depth intervals exceeding 10 ft (3 m) or more. Sampling and handling disturbance may also significantly reduce the accuracy of the results. In general, the authors believe that in-situ testing provides more information, more quickly, with less cost.

Standard Penetration Test (SPT): Tests are commonly performed on 5-foot (1.5-meter) depth intervals at several borehole locations on a site. Because each boring could serve as a settlement prediction, there are usually enough data for numeric probability analyses. The test measures the number of hammer blows (N value) to drive a sampler 1 ft (0.30 m) into the soil. There are several acceptable hammer types, but these different hammer systems deliver different energies to the sampler. Unfortunately, the energy is rarely measured in the United States. (The new standard in Europe requires energy measurement.) The hammer energy transferred to the rods, when measured, varies from 30 to 95% of the theoretical potential energy of 4200 in-lb (475 N-m). The hammer type, while a critical factor for the energy, is often omitted from the boring log. If the geotechnical engineer does not know the energy used to drive the sampler, this significantly reduces the accuracy of any N-value interpretation.

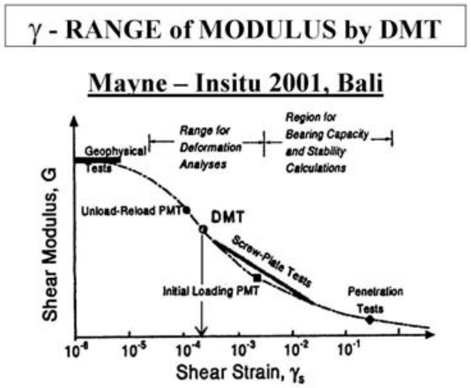

FIG. 1 Comparison of strain levels of in-situ tests and structures

The SPT is a dynamic penetration strength test and strains the soil to failure. As shown on Fig. 1, structural loads commonly strain the soil to intermediate levels. To determine the soil deformation modulus from the SPT N-value requires extrapolation from a strength parameter at failure strain to a deformation parameter at an intermediate strain, another possible source of error.

The dynamic penetration of the sampler in cohesive soil, especially sensitive soil, remolds the soil. In residual soils, the SPT destroys the latent rock structure. In both cases N-value correlations for the static deformation modulus are very poor or invalid. In sands, modulus correlations are somewhat better. Duncan (2010) suggests a relatively high coefficient of variation for the accuracy of predicting settlement in sands using N_{60} values (N-value with energy corrected for 60% of the theoretical energy) of 0.67. In a perfectly homogeneous soil, the error in the method alone would require that the average value of settlement be 0.30 in (7.6 mm) to be 95% certain that a settlement of 1.00 in (25.4 mm) would not be exceeded. Therefore, even the best case scenario for the SPT, seems much too inaccurate to predict settlement.

Cone penetrometer tests (CPT): The CPT measures the tip resistance (q_T) using calibrated strain gauges, typically providing repeatable data at 0.03 to 0.16 ft (0.01 to 0.05 m) depth intervals. Therefore, there are sufficient data to quantify risk. Like the SPT, the test strains the soil to failure. While the quasi-static tip resistance, q_T, has reasonable accuracy and repeatability, the engineer must still extrapolate to a deformation modulus at an intermediate strain level. The commonly-used equation below relates the tangent modulus, M, to q_T, using a strength parameter to predict a deformation parameter.

$$M = (\alpha)\,(q_T),$$

Depending on stress history and soil type, the value of α ranges from 1 to 8 for cohesive soil, 3 to 11 for normally-consolidated sand, and 5 to 30 for over-consolidated sand. Most engineers use conservatively low values and tend to over predict settlement. The unknown range of α reduces the accuracy of settlement prediction from the CPT.

Pressuremeter tests (PMT): The pressuremeter test strains the soil to intermediate strains in static deformation. Thus, the PMT predicts settlement relatively well, though often relying on empirical methods. However, it is a relatively slow test to perform and typically only two to six tests can be performed in one day, often at depth intervals of 10 ft (3 m) or more. The quantity and the quality of the tests are highly dependent on the driller’s skill and experience. Unfortunately, there are usually not enough tests performed for a risk assessment of settlement.

Dilatometer tests (DMT): Like the pressuremeter, the dilatometer uses static deformation to strain the soil to intermediate strains. The DMT provides the one-dimensional tangent modulus (M) with tests generally performed at depth intervals of 0.66 ft (0.20 m). In thin layers of compressible soils, tests are often performed at depth intervals of 0.33 ft (0.10 m) for better definition. Tests typically take about 1 minute to perform and a sounding provides sufficient data for risk assessment of settlement with DMT. The authors recommend the dilatometer test as the best choice of in-situ tests for the settlement prediction of shallow foundations. At numerous (20+) sites in a wide variety of soils, Schmertmann (1986) and Hayes (1986) separately predicted settlement using DMT and measured actual settlement of footings/embankments. With the exception of quick silts, they found a ratio of predicted to measured settlement of 1.07 with a coefficient of variation of 0.18 (Failmezger, Bullock, 2004).

OWNER'S EXPECTATIONS FOR DESIGN SERVICES

The engineer must perform design services to meet the standard of care, i.e. the level of service provided by an average engineer in the geographical area at the time of service. The engineer carries professional liability insurance that covers the risk only when his services do not satisfy the standard of care.

However, many owners want better than average design services. They want the engineer to design the foundation as economically as possible while safely supporting the structure. They want their structure to perform as intended, but they do not want to spend unnecessary money on the foundation. To perform a higher level of services, the engineer must perform a more sophisticated subsurface investigation that accurately quantifies the soils' deformation properties. A thorough investigation increases the engineer's knowledge and reduces the uncertainty of the design parameters of the soil, improving the accuracy of settlement estimates.

Smaller foundations generally settle more than larger ones. The owner must choose between the cost savings of a smaller foundation and the increased risks for unsatisfactory performance (e.g. cracks). Provided that the foundation is stable, the cost to repair any initial cracking is often far less expensive than the additional cost of an overly conservative foundation.

The owner's expectation of the engineer's service exceeds the level of service covered by professional liability insurance. The owner benefits financially from the better design services by having a smaller and less expensive foundation and logically should be the party to take this additional liability.

PREVALENT U.S.SHALLOW FOUNDATION DESIGN

The geotechnical engineer typically performs several standard penetration test (SPT) borings across the site, obtaining samples only for soil identification, gradation, Atterberg limits. Based on the engineer's experience, the SPT N-values, and limited lab data, the engineer then recommends an allowable bearing capacity, rounded to the nearest 500 psf (23.9 kPa), to the structural engineer for design. All footings are then sized based on this single design bearing capacity.

The column loads for the structure can vary considerably, requiring larger footings for heavier loads. A larger footing load strains a larger and deeper volume of soil with greater settlement. While the deformation properties of the underlying soil can vary significantly within the site, the engineer does not directly measure them and has relatively coarsely spaced data with which to work. The inherent variability in the field measurement of the N-value combined with a relatively crude design method leads to highly inaccurate settlement predictions using the SPT. Faced with so much uncertainty, the engineer typically recommends an overly conservative and expensive design.

IMPROVED SHALLOW FOUNDATION DESIGN

Dilatometer tests can help significantly reduce design uncertainty by providing depth profiles of repeatable and accurate deformation modulus values. Typically, the goal of foundation design is to minimize the settlement between any two points on the structure relative to the distance between them, or the angular distortions, to avoid unacceptable damage to the structure. Table 1 shows limits of angular distortion for different types of structures and their uses. The geotechnical engineer, the owner and structural engineer, working closely together, should choose the appropriate risk levels for angular distortion.

Table 1 Allowable Angular Distortion

Situation	Allowable Angular Distortion
Machinery sensitive to settlement	1/750
No cracking in buildings; tilt of bridge abutments; tall slender structures such a stacks, silos, and water tanks on a rigid mat; steel or reinforced concrete frame with brick block, plaster or stucco finish and length to height ratio greater than 5	1/500
Cracking in panel walls; problems with overhead cranes	1/300
Structural damage in buildings; flexible brick walls with length to height ratio greater than 4	1/150

The design procedure has the following steps:

1. Perform dilatometer soundings at the site,
2. Perform settlement calculations for each column,
3. Calculate the angular distortion between adjacent columns,
4. Determine the average and standard deviation values of angular distortion for the structure,
5. Quantify the standard deviation values from other sources of error,
6. Compute the overall standard deviation value for angular distortion,
7. Plot the average and overall standard values on the probability angular distortion design charts and determine if the design is satisfactory.

Perform dilatometer soundings: Perform DMT soundings to accurately characterize deformation properties at the site, focusing on weaker soils when encountered. Generally, perform soundings at the heavier column loads and at some of the perimeter columns. For columns, the sounding depths should extend at least two times the design footing width to define the modulus values within the footing's stress bulb. For wall footings, the depth should extend least four times the footing width. Both cases require additional depth where footing influence overlaps, and several deep soundings should be used to identify soft soils that may cause global settlement of the structure. Sites with heterogeneous deformation properties require more DMT soundings for proper site characterization.

Settlement Calculations: From each dilatometer sounding, the engineer predicts settlement using Schmertmann's method, multiplying the tangent modulus by the predicted elastic stress at depth increments equal to the DMT test interval. The load for the settlement calculation includes the column load, which lessens with increasing depth (stress bulb) and the weight of any additional fill, which is typically assumed infinitely large horizontally and imposes a uniform pressure to infinite depth. The engineer adjusts the footing dimensions so that settlement for the structure is as uniform as possible.

A settlement prediction must be made for each column. If there is no DMT sounding at the column location, then a weighted average settlement can be computed from the nearby DMT soundings. With this approach, the horizontal distance from each nearby DMT sounding to the column is calculated. The total distance of all nearby soundings is summed. The contributing settlement from a sounding equals the predicted settlement times its distance divided by the total distance. The predicted settlement for the column is the sum of the contributing settlements. The weighted average method only works if the soils' deformation properties do not significantly change between soundings. If there is significant variability, then a DMT sounding must be conducted at that column location.

Angular Distortion: The angular distortion is computed for all adjacent columns by dividing the predicted settlement difference or differential settlement by the horizontal distance between the columns. Any large values of angular distortion require a redesign for those footing dimensions to reduce the differential settlement.

Computing Average and Standard Deviation of Angular Distortion: Each value of computed angular distortion becomes part of the angular distortion data set. The average and standard deviation are calculated from this data set. The computed standard deviation represents the predicted settlement variability and accounts for the variability of the deformation modulus properties of the soil at the site.

Other Sources of Error: Other error sources include the accuracy of the Schmertmann DMT settlement method, the accuracy of the column loads, how well the contractor constructs the footings, and how well the inspector monitors the footing construction. From case study data, Failmezger and Bullock (2004) determined a coefficient of variation for Schmertmann's method of 0.18 for all soils except quick silts with an average predicted settlement 1.07 times the measured value. While the structural engineer can accurately predict the dead load of the column, he or she cannot accurately predict the live load. The structural engineer should provide the coefficient of variation for the column loads. The engineer must judge contractor and inspector error based on their qualifications, with a reduction for better expertise and a penalty for lower cost.

Overall Standard Deviation of Angular Distortion: If the sources of error are independent of each other, then the overall standard deviation is computed as the square root of the sum each standard deviation squared. This is the maximum or conservative value of standard deviation. If these sources of error are partially dependent on each other, then a lower value of standard deviation could be used.

ANGULAR DISTORTION DESIGN CHARTS

The Beta probability distribution was chosen to determine the risk of angular distortion exceeding acceptable limits. The normal probability distribution was not used because its minimum/maximum end limits are negative infinity and positive infinity, both unrealistic. The log-normal probability distribution was not used because its end limits are zero and positive infinity, and positive infinity was unrealistic. The minimum and maximum end limits of the beta distribution are selected by the user and the authors chose the limits as ± three standard deviations from the mean. The minimum end limit was the larger of zero or the computed value. When the minimum end limit was greater than zero, the distribution was not skewed; when it was zero, the distribution was skewed right.

The area under a probability distribution curve is defined as 1.00. The area where the probability curve exceeds the angular distortion limit is the probability of failure. The probability of success is therefore 1.00 minus the probability of failure. The probabilities of success of 90%, 95%, 99%, and 99.9% were calculated for angular distortion limits of 1/750, 1/500, 1/300 and 1/150 for the average and overall standard deviation values of angular distortion. Plots of the average and standard deviation for those probabilities of successes are shown as Figs. 2 to 5 for limits of 1/750, 1/500, 1/300 and 1/150. If the probability distribution curve was bell-shaped and not skewed, then the relationship between the average value and standard deviation was linear. If the distribution curve became skewed right, then the relationship became non-linear.

Example Problem: The owner plans to construct a four story reinforced concrete office building with drywall interior walls. He desires probabilities of success of 99.99% against structural damage and 95% against drywall cracking. The geotechnical engineer performs dilatometer soundings at most of the column locations and determines the average value of angular distortion of 0.0022 and a standard deviation of 0.0002. The coefficient of variation for the dilatometer prediction method = 0.18 (case study database); for the loads = 0.20 (provided by the structural engineer); for the contractor/inspector = 0.10 (selected by qualifications). The standard deviation equals the coefficient of variation times the average value of angular distortion. Therefore, the standard deviation for the DMT method = 0.0040, for the loads = 0.0044, and for the contractor/inspector = 0.0022. The overall standard deviation was 0.0063. By plotting the average and overall standard deviation values on Fig. 4, we estimate a 96% probability of success. These values plot significantly to the left of the 99.99% line on Fig. 5. Therefore, the design satisfies the owners' needs.

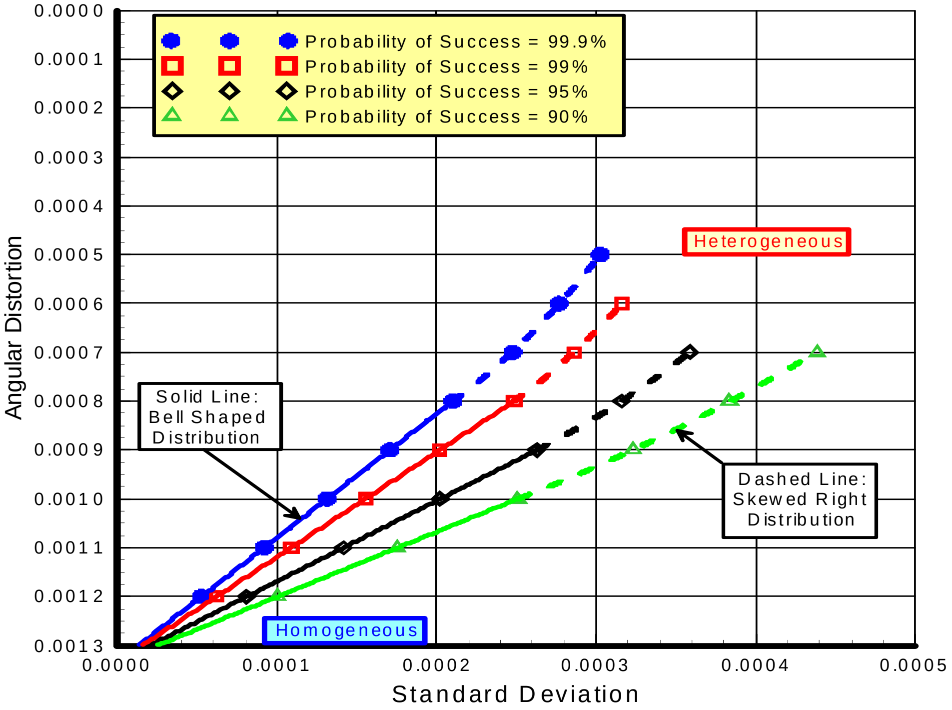

FIG. 2 Threshold Value of Angular Distortion = 1/750

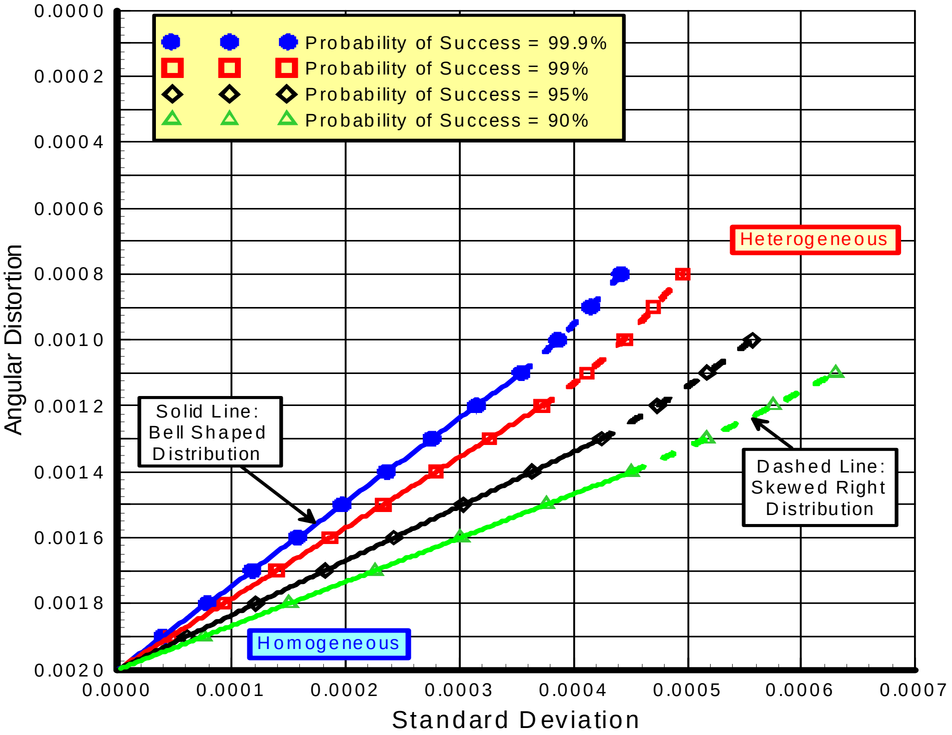

FIG. 3 Threshold Value of Angular Distortion = 1/500

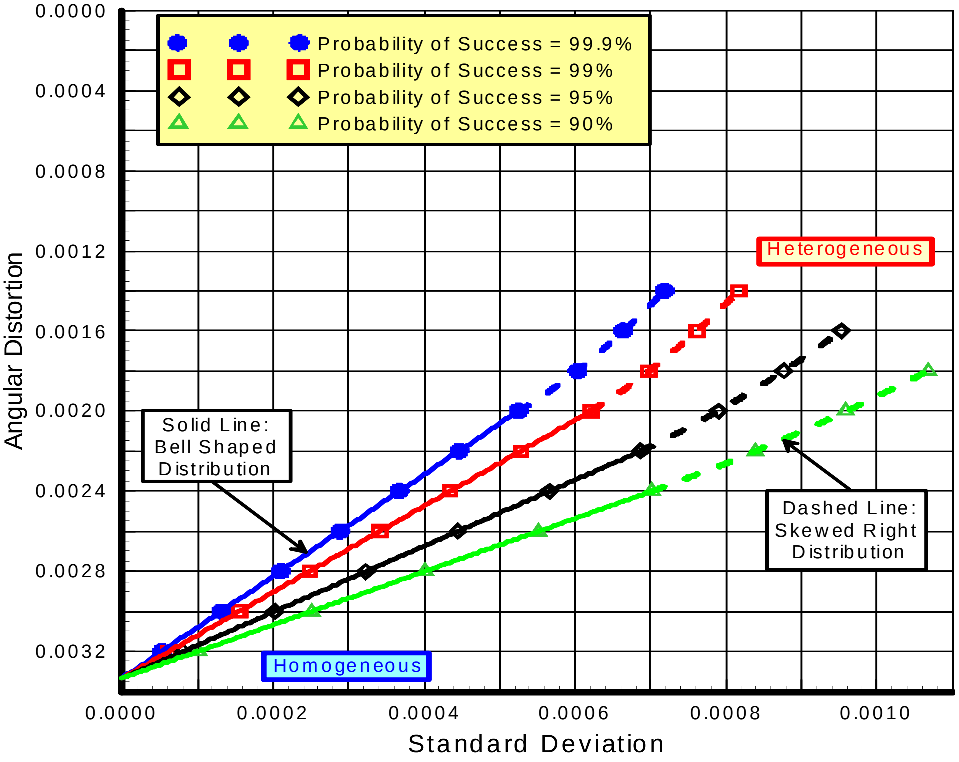

FIG. 4 Threshold Value of Angular Distortion = 1/300

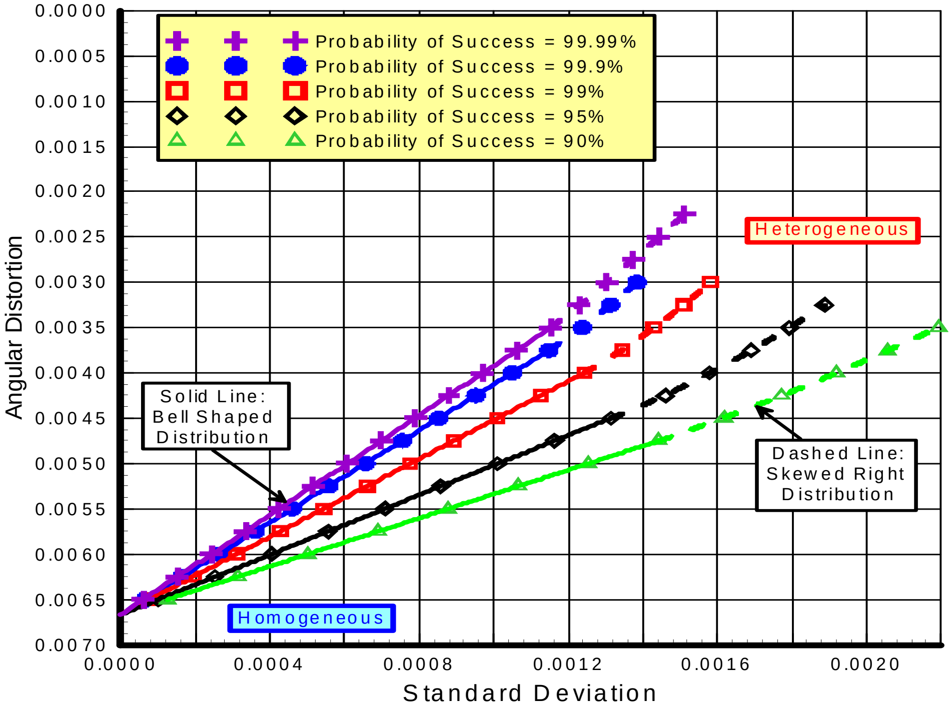

FIG. 5 Threshold Value of Angular Distortion = 1/150

CONCLUSIONS

1. For structures with intermediate to heavy loads or sites with heterogeneous subsurface conditions, the owner will financially benefit from a thorough subsurface investigation and a detailed settlement analysis for angular distortion of the shallow foundation system. With the proposed shallow foundation design method, the engineer can often design buildings to be safely supported on shallow foundations that otherwise may have been designed with deep foundations.
2. The relationship between the average and standard deviation of angular distortion for different probabilities of success is linear if the probability distribution curve is bell-shaped.
3. The owner can select the level of risk for angular distortion and balance the lower costs of an economical shallow foundation and the higher risk of angular distortion.
4. The authors do not recommend using SPT data for settlement predictions due to its inherent variability and the correlation required between N-value and deformation modulus.
5. The authors do recommend using DMT data to directly measure deformation modulus for risk assessment of shallow foundations.

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