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Computational Investigations of Concrete Footing Rotational Rigidity

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***Abstract*—**In many buildings we rely on large footings to offer structural stability. Designers often compensate for the lack of knowledge available with regard to foundation-soil interaction by furnishing structures with overly large footings. This may lead to a significant increase in building expenditures if many large foundations are present. This paper describes the interface material law that governs the behavior along the contact surface of adjacent materials, and the behavior of a large foundation under ultimate limit loading. A case study is chosen that represents a common foundation-soil system frequently used in general practice and therefore relevant to other structures. Investigations include compressing versus uplifting wind forces, alterations to the foundation size and subgrade compositions, the role of the slab stiffness and presence and the effect of commonly used structural joints and connections. These investigations aim to provide the reader with an objective design approach, efficiently preventing structural instability.

***Keywords*—**Computational investigation of footing rotation.

I. Introduction

STRUCTRAL characteristics of concrete column-foundation systems embedded in compacted soils or gravels and various subgrades, and the interaction between them, such as load distribution characteristics, inelastic response, and ultimate strength; cannot be calculated realistically with simple procedures currently used in design and evaluation. Experimental tests are at times time consuming and expensive, depending on the number of specimens and parameters required for an investigation. If properly conducted, comprehensive numerical studies can provide reliable estimates of response of such structures, eliminating the necessity for extensive physical experimental tests for these systems. Nonlinear finite element analysis is thus used in this study to predict and detail the behavior of large foundations under loading and the interaction with its soil surroundings. In order to create a study that has relevance to its field of practice, the design of an aluminum foil finishing plant received from Mr Gerrit Bastiaanse of BKS was used to determine initial geometrical dimensions, loading and soil structure of a typical industrial building. In order to broaden the relevance of the study to foundations experiencing different failure conditions. This particular case is an example of a commonly used structure and allows the investigation to be relevant to similar industrial buildings. By considering a representative column-foundation system allows for the easy adaptation of a finite element model to new dimensions, loads and material parameters.

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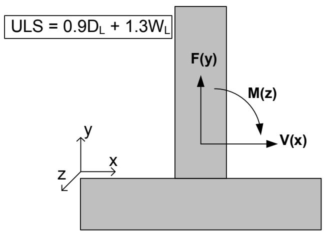
II. Framework of Study

A. Background

This study investigates a foundation-soil system typically found in industrial buildings with slender columns and large open spans. The study broadens its scope to include foundations under uplifting and compressing wind forces, shown in Fig. 1, as would be found in the case of a light and a heavy weight structure respectively. It explores the impact of varying subgrade materials covering a range of high to low stiffness types. The foundation size is increased and decreased, the grade of concrete used for the slab is lowered and the effect of commonly used movement joints and a joint filler material is considered.



LIGHT STRUCTURE

	V(x) (kN)	F(y) (kN)	M(z) (kNm)
Dead load	0	-500	0
Wind load	200	850	500

HEAVY STRUCTURE

	V(x) (kN)	F(y) (kN)	M(z) (kNm)
Dead load	0	-1000	0
Wind load	200	-850	500

Fig. 1 The layout of ultimate limit state column reaction forces and moments

B. Limitations of Study

Three typical failure possibilities are not included in this study and are considered the responsibility of the design engineer to provide for these possible failure patterns.

1) The first requirement of the designer is to be sure that the self weight of the structure and foundation is larger than an uplifting wind load. The foundation should therefore be sufficiently heavy to prevent itself from separating from the subgrade directly beneath it. The point of uplift under increasing load increments will be indicated by the delamination of the interface elements along the base of the

foundation. The designer should therefore not rely on the slab to offer any resistance against overall foundation uplift as this event will in this study be considered a point of failure.

2) A second condition the designer needs to take into account prior to considering the outcomes of this study is to verify the overturning stability of the foundation. The foundation needs to be deep enough and have a width capable of withstanding rigid overturning forces and moments.
3) A third a final failure criterion the designer needs to account for is the cracking of the column or foundation. These cracks would cause a hinge effect and has the potential of greatly increasing displacements and rotations and may overshadow the outcomes of this study. It is therefore assumed in all investigations in this study that column will not tear off from the foundation under large moments or that the foundation will split under the same loading.

C. Objectives of Study

The overall objective of this investigation is to gain a better understanding of the behavior of fixed concrete foundations and their interaction with their surrounding material under various realistic and critical loading situations. Specific focus is placed on calculating the rotation of foundations in all of the models investigated. This interest is due to the potential failure caused by lateral displacement at the top of the column resulting from a tilting action of the foundation when rotating. Combined with compressive axial loads, increased moments can be experienced within the column and thus the foundation. This can in turn result in overturning moments causing an even more severe case of overturning of the column, leading to failure.

D. Method of Investigation

Nonlinear finite element models are evaluated and subsequently used to examine the structural behavior of a foundation under loading and to create interfacial bond elements that depict the interaction of the foundation with its surrounding materials. A sensitivity study is performed varying foundation geometry, loading, strength of concrete, and stiffness of the subgrades to establish a pattern of behavior applicable to a broad range of foundation types. The contact problem between a concrete foundation and soil is approached by means of a DIANA [1] interface model with multi-surface plasticity. The foundation-soil interface has a very low tensile bond/adhesive strength and high compressive strengths. The model has the capability to simulate these phenomena and is also capable of simulating gradual reduction in resistance, or softening, after the maximum bond strength has been exceeded. Furthermore the model also takes into account friction forces which arise on the contact surface between soil and concrete. Nonlinear analyses of an embedded concrete foundation, based on a finite element model capable of simulating evolving behavior of the foundation and soil, as well as the evaluation of ultimate limit state loads, are purposed.

III. Finite Element Model

As physical experiments fall beyond the scope of the thesis, it is decided in this study to create a three-dimensional model of the structure to be used as a reference for a simplified two-dimensional model. This is because the three-dimensional model is considered to be a more accurate representation of the structure and will therefore more holistically represent its behavior. The reasons for these accuracies and the conversion method purposed by the author [2] discussed in a more extensive body of work.

The surface between the concrete of the foundation and column, and the soil with which it comes into contact, is of particular interest. An interface element is assembled to capture the behavior of this boundary. Interface elements are also placed along the contact surface between the slab and column. No interface elements are positioned between the contact surface of the slab and soil. This is done to simplify the model and thus reduce analysis time as fewer complex nonlinear interface elements will lead to more rapid convergence of load increments applied to the model. This design is considered to be acceptably representative of the column-foundation system as the focal point of this study lies with the displacements and rotations of the foundation and column. For the uplift and separation of the slab from the soil to occur, foundation displacements will be of the nature to cause serious concern and will receive urgent interest, leaving the slab comparatively overlooked due to its less severe qualities. A layer of interface elements surrounding the foundation and column are therefore sufficient for the purposes of this study and elements between the slab and soil deemed unnecessary.

A. Dimensions and Material Properties

The dimensions of the reference column, foundation and subgrades are obtained from the drawings of the aluminum foil finishing plant. The challenge however is in determining the outer boundaries of the model; that is, it had to be decided how far around and below the foundation the soil would react against pressures from the structure. It has to be ensured that the foundation behavior is not subjected to boundary conditions in an unrealistic way. These boundaries depend on several material properties of the soil and the dimensions of the foundation. This entails the bearing capacity of the soil and the type of failure most probable to the type of soil at hand. General shear failure is typical of soils of low compressibility, i.e. dense or stiff soils such as sand or compacted gravel. A suitable failure mechanism for a strip footing is shown in Fig. 2.

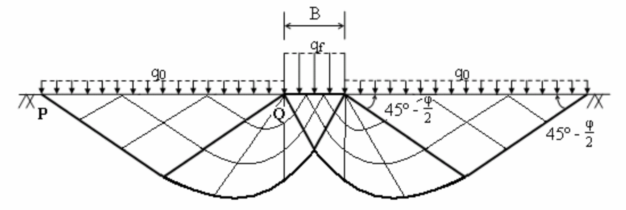


Fig. 2 Typical patterns of slip-lines in the soil beneath a foundation

The distance from points P to Q for a known angle of shearing resistance φ′ and for a foundation breadth B, can be calculated as follows:

$$PQ = B\exp[\frac{\pi}{2}\tan\varphi]\tan(\pi/4+\varphi/2) \quad (1)$$

For a known breadth B, a depth beyond which no further significant exertions upon the soil are present, can also be found as shown in Fig. 3 below.

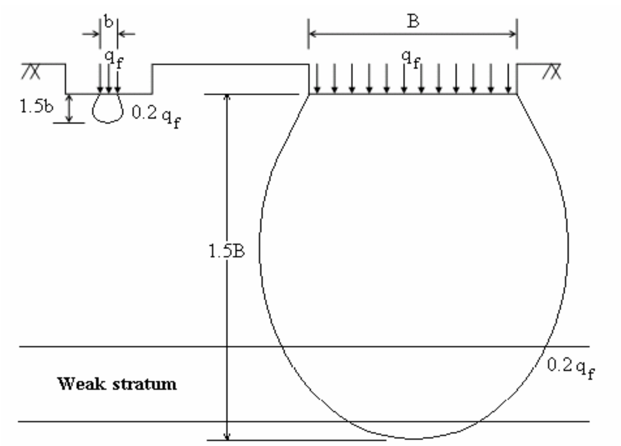


Fig. 3 Typical patterns of stress distribution in the soil beneath a foundation [3]

The geometrical soil boundaries for the numerical investigation of any foundation can therefore be determined for a known foundation breadth and angle of shear resistance. The material properties are given in Table I below from which these boundaries can be determined.

TABLE I
MATERIAL PROPERTIES OF THE FOUNDATION-SUBGRADE SYSTEM [4]

	CONCRETE	CEMENTED GRAVEL (C3)	COMPACTED GRAVEL (G7)	IN-SITU CLAY
Elasticity Modulus	30 GPa	2 GPa	100 MPa	10 MPa
Poisson (μ)	0.2	0.2	0.35	0.3
Density (kg/m^3)	2400	2000	1650	1900
Friction Angle (φ)	-	0	0	35°
Shear Strength	-	-	20 kPa	10 kPa

The dimensions that follow this particular system are shown in Fig. 4 below. The layer of interface elements modeled along the contact surface between the column-foundation system and the soil is 1 mm thick.

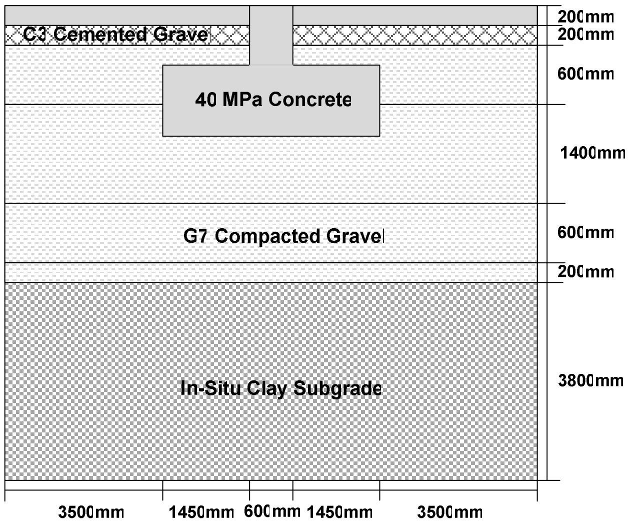


Fig. 4 The geometrical dimensions of the Finite Element model

B. Model Elements

All concrete and soil materials in the structure are modeled with isoparametric continuum elements for both two- and three-dimensional investigations. The boundary where these materials meet is modeled with structural interface elements. For the two-dimensional model, four-node quadrilateral isoparametric plane stress elements are used for the concrete and soil components of the model while eight-node isoparametric solid brick elements are used in the three-dimensional model. In the two-dimensional model the structural interface element is of the configuration of a two-by-two line between two lines, that is, the interface element is aligned between neighboring 4 noded elements, and for the three-dimensional model the configuration of a 4 by 4 quadrilateral plane between two planes is aligned between neighboring 8 noded elements.

C. Mesh Density

The finite element mesh is more refined directly around the foundation and column areas and less so towards the model boundaries. The layer of clay below the compacted materials is also coarser, comprised of larger and more rectangular elements. For the elements to have reasonable deformation behavior, the ratio of the sides of an element was kept within a one to four relationship. These rectangular shaped elements allow the use of larger and thus fewer elements towards the edges of the model and in areas of less interest. The layout of the mesh is shown in Fig. 5.

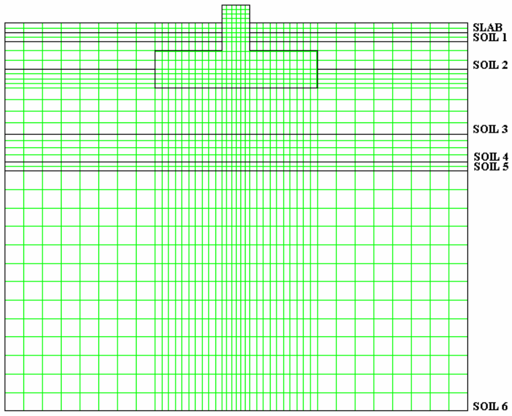


Fig. 5 A two-dimensional layout of the mesh for the complete model

IV. Interface Material Law

Processes and mechanisms of contact interaction are modeled numerically, approximating the interface with finite elements of a minimal thickness. Since these elements should define the shear and normal stresses on the boundary of the dissimilar materials, their mechanical and strength characteristics should reflect the properties along the slip boundary and not necessarily correspond to those of the adjacent materials.

Associated with computational investigations of the interaction between a soil mass and components of engineering structures, are the modeling of non-linear processes such as slip or separation, on the interface between the structure and soil. The analysis of a soil-concrete system is complicated by the interface between the structure and soil. To simulate the interaction between the soil and foundation under the application of various loads, the appropriate characteristics of an interface element needed to be captured. Concrete and soil particles in contact with one another may need an initial force to induce slipping, after which only a small amount of force is needed to maintain slipping. Upon the application of an additional critical compressive force, the particles may first crush before continuing to slip/grind. An interface model appropriate to simulate fracture, frictional slip as well as crushing along interfaces is needed.

A plasticity based multi-surface interface model formulated by Lourenço and Rots [5], also known as the 'Composite Interface model' or combined cracking-shearing-crushing interface model, is prescribed in this study. This model consists of a Coulomb friction model combined with a tension cut-off and an elliptical compression cap (see Fig. 6).

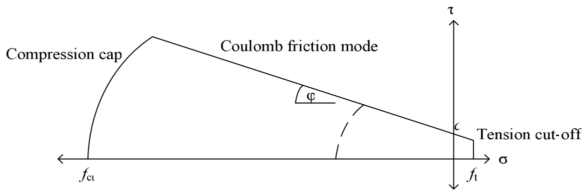


Fig. 6 Composite yield surface

The elastic domain is bounded by a composite yield surface that includes compression, tension and shear failure. Softening acts in all three modes. This softening is governed by tensile fracture energy G^{I}_{f}, shearing fracture energy G^{II}_{f}, and compressive fracture energy G^{III}_{f}. Hardening of the cap precedes softening degradation.

Exponential tension and shear softening curves with a Mode I fracture energy G^{I}_{f} and Mode II fracture energy G^{II}_{f} respectively, depict the material law described. For compression, the fracture energy is the geometrical area found under the softening curve. It is only the area illustrated by plastic deformation and does not include the elastic deformation. The same applies for shear. If there is however a confining pressure on the element, there will be a peak resistance of $c - \varphi\sigma$ and a residual resistance equal to $- \varphi\sigma$. The fracture energy will exclude this residual stress level. All fracture energies are shown in Fig. 7 below. Note that, for computational convenience, DIANA [1] uses a small residual compressive resistance, as shown in Fig. 7. Also in this case the energy excludes the residual value.

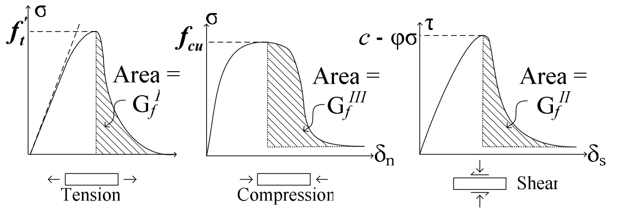


Fig. 7 Interface traction-displacement behavior in various stress states

In typical concrete-soil interaction, and especially when the soil is of a sandy or gravel composition as in this case study, the soil will separate from the concrete under a very low tensile force, resulting in de-bonding and consequently, under lateral loading, shear-slipping. The material properties of the interface model are chosen in a manner in which the tensile forces the structures can exert on one another are negligible compared to their compressive strengths, as found using simple, single element tests. To allow the numerical overlapping of neighboring particles to be negligible, high stiffness values of for the normal modulus k_n and shear modulus k_s are chosen. The inelastic properties of the interface are shown in Table II and the tensile and shear fracture energies, G^{I}_{f} and G^{II}_{f} respectively, are chosen by observing the effect on the softening curve through an iterative process.

TABLE II
Inelastic Properties of the Interface Model

Values determined through simulations on a single interface element		
Normal modulus	k_n	2×10^5 N/mm^3
Shear modulus	k_s	2×10^4 N/mm^3
Compressive strength	f_{cu}	1.0e10 N/mm^2
Tensile strength	f_t	0.01 N/mm^2
Cohesion	c	0.02 N/mm^2
Friction coefficient	φ	0.5

V. Confirmation of Modeling Decisions

Before continuing with further investigations, some assumptions made in the modeling of this structure are verified next. The decision to exclude soil and subgrade settlement and plasticity is scrutinized in this section to be sure that their absence will not affect the accuracy and reliability of this study. This section contains the findings of either more complex analyses or the complete examination of current models as to validate assumptions made.

A. Phased Analysis

A phased analysis of the structure is performed to scrutinize the assumptions of the boundary conditions where all model edges are pinned against translation in all directions. The settlement of soil and subgrade prior to the presence of a wind load is investigated to determine the effect, if any, on the rotation of the foundation. In this analysis the loading on the finite element model is divided into 3 phases. An initial settlement of the soil is allowed without the restriction of vertical displacements. In the second phase all edges of the model are again pinned against all translations. The dead weight of the structure and own weight of the slab and foundation are applied in this phase. In the third and final phase the boundary conditions remain as in phase two and the loads and moments caused by wind are imposed on the model.

In phase one, a large amount of settlement takes place in the absence of the vertical constraints. Settlement around the foundation is symmetric and does not influence the rotational behavior of the foundation. The same applies for the second phase as the self weight of the structure alone does not cause any rotation of the foundation. Finally, in the third phase, the foundation start to rotate under the application of overturning wind loads. The amount of rotation that takes place remains very similar to that of a single phase analysis. With a difference in rotation of between two and three percent between a three-phased and single phase analysis, the latter being the more conservative, it can be concluded that the settlement of soil plays no significant role in the mechanics that prevent or cause rotation of the foundation. As the phased analysis is considerably more time consuming due to convergence difficulties, the single phase analysis, the model described in section 2, will be used for all further investigations.

B. Testing of Soil Capacity

The decision to use linear elastic modeling for the soil is validated here by confirming that the bearing capacity of the soil is not exceeded. If a slip plane were to develop, the rotation of the foundation could potentially increase drastically. As the heavy structure offers more downward pressure on the subgrades, it would test the bearing capacity of the soil more severely than the lighter structure and is therefore the model used in the examinations in this section. The bearing capacities of the materials used are given in Table III [3].

TABLE III
Bearing Capacities of Materials Used

	Concrete	Cemented Gravel (C3)	Compacted Gravel (G7)	In-situ Clay
Bearing Capacity (kPa)	40000	2000	200-600	75-150

At 12 times the ultimate limit load the bearing capacity of the soil is not yet exceeded. In the following section, various combinations of subgrade materials are investigated. The bearing capacity of the subgrade with the lowest stiffness is not exceeded for one times the ultimate load and only at 7 times the ultimate load is the upper limit exceeded. As will be explained in the next section, this subgrade combination is an extreme case and is not commonly found in reality. All other subgrade combinations were confirmed capable of bearing the loaded foundation for 12 times the ultimate limit load. It is therefore concluded that the decision to exclude the plasticity of the soil in investigations is acceptable for the purposes of this study.

VI. Factors Contributing To Foundation Rotation

This section aims to generalize the behavior of such structures by investigating factors that effect the rotation of the foundation. Such factors included the materials properties of the subgrades present, the size of the foundation, and more that will be discussed in the sections to follow.

A. A Variation of Subgrade Materials

Few elements of a foundation-soil system would effect deformations and displacements as much as the material properties of the subgrade. Three alternatives to the subgrade layout previously described are chosen and are discussed in this section:

1) In a case of lower subgrade stiffness there is no G7 compacted gravel present but instead only the in-situ clay subgrade directly below the C3 cemented layer.
2) In the case of a higher stiffness the G7 compacted gravel is replaced with C3 cemented gravel which lies three meters deep starting directly below the slab. The actual construction of such a subgrade would be very expensive but the purpose of the investigation is to consider the effect of a more stiff material than currently prescribed.
3) The third alternative investigated is near exactly the original subgrade specifications, but with an additional two-hundred millimeter layer of C3 cemented gravel directly beneath the foundation.

The wind load is applied to structure up to nine times that of the ultimate load. The rotation of the foundation is plotted against the corresponding load factor in Fig. 8 for all the subgrade variations discussed.

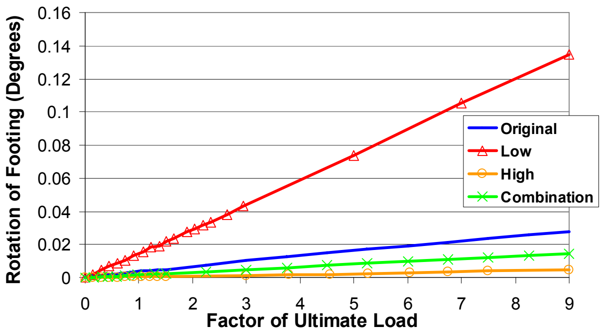


Fig. 8 Rotation versus ultimate load factor for a variation of subgrade stiffness

The most apparent change in foundation behavior in terms of rotation is the enormous increase in rotation found when replacing the G7 compacted gravel with in-situ clay. This drop in stiffness causes rotation of the foundation that is 5 times higher than that of the original soil stiffness. By adding a layer of C3 cemented gravel to lie directly below the foundation, the rotation of the foundation is halved. With the expensive alternative of using only C3 cemented gravel instead of G7 compacted gravel, the rotation can be reduced 6 times. It can be concluded that in a case where rotation of the foundation is contributing to structural instability, a thin layer of stiff material directly below the foundation is a cost-effective way to significantly reduce rotation.

B. Changes in Foundation Size

One of the factors influencing the rotation of the foundation under a constant load is its size. A smaller foundation is expected to rotate more than a larger one. This is due to the decrease in the contact area between the concrete and soil providing less frictional resistance, and the reduction of resistance to a constant moment carried to the foundation via the column. If the foundation width is reduced, resistance forces at the corners will need to be larger to prevent more rotation than before. As the subgrade is not infinitely stiff, larger deformations than before will be a result and more rotation will therefore occur.

1) Original Subgrade

The theory above is confirmed by studying Fig. 9. It can clearly be seen how the delamination of the interface elements increases from a foundation of a 4 meter width to one of 1.75 meters. The increase in delamination of the interface is due to a larger sinking of the foundation under the compressive dead weight of the structure above, and less resistance to rotation as the foundation decreases in size.

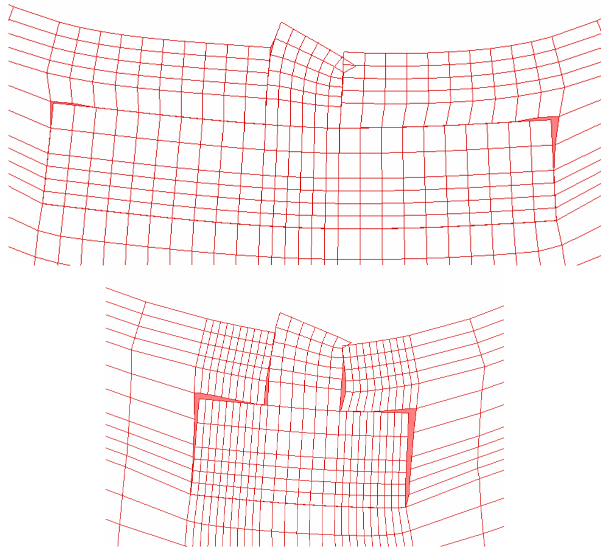


Fig. 9 Delamination of interface elements for the 4m and the 1.75m footings for the ultimate load viewed at a magnification factor of 500

The rotation versus factor of ultimate limit loading is plotted in Fig. 10 for the original foundation width of 3.5 meters, and is accompanied by the plots of a 4 meter and a 1.75 meter foundation. A new finite element model boundary perimeter has to be calculated for each new foundation using equation 1.

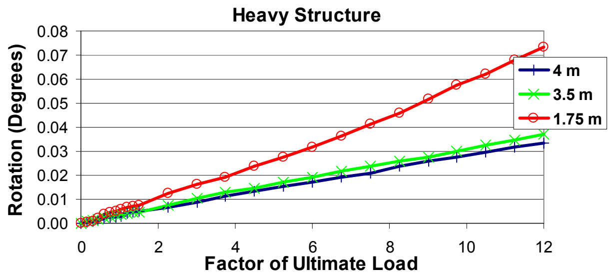


Fig. 10 Rotation versus ultimate load factor for a variation of foundation widths

It can clearly be seen how the rotation decreases for a larger foundation and increases for a smaller one. The upward curling plot of the smallest foundation shows that it increases more rapidly than the larger foundations with linearly increasing plots. This behavior is confirmed for the light structure as a rotation-load plot similar to that of the heavy structure, shown above, is constructed using test results for foundations of various sizes under uplifting wind forces. The factor of the ultimate load is limited to the region just after the foundation starts to lift up off the subgrade below, indicated by the black dots on the plot in Fig. 11. The finite element model in not sufficiently designed to consider uplifting and further results would be inaccurate. It is also a scenario which must be prevented by the designer; the footing weight together with other permanent loading must provide sufficient anchorage to prevent uplift.

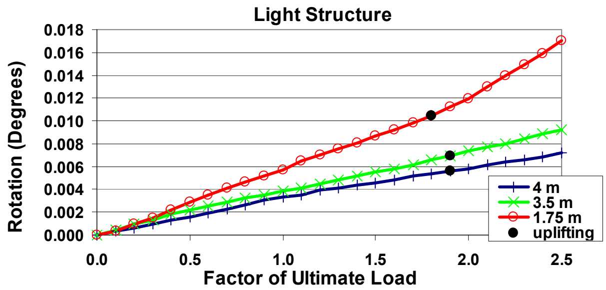


Fig. 11 Rotation versus ultimate load factor for a variation of foundation widths

It can also be concluded that not only does a smaller foundation rotate more; it will lift up earlier under an uplifting wind load, as can be seen from the figure above. The opposite is also true for a compressive load where it was found that the smaller foundation sinks into the subgrade sooner than a larger one. This could be seen in Fig. 9 above judging from the delamination of the interface and gradient of the slab.

2) Other Subgrade Combinations

The same behavior is found for all other subgrade combinations as for the original subgrade. The amount of rotation for each foundation at one times the ultimate wind load is plotted in Fig. 12.

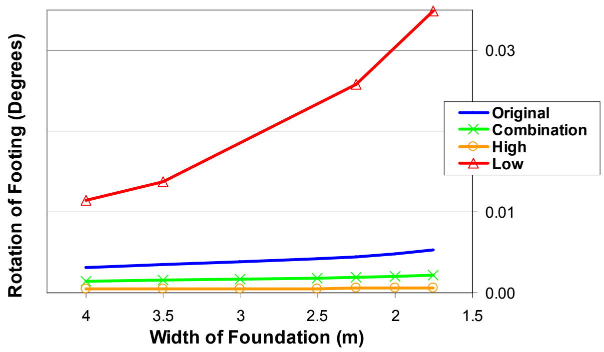


Fig.12 Rotation of various foundations sizes for all subgrade combinations

Smaller foundations rotate sooner and more rapidly and the reduction of foundation size leads to speedier rotations. The effect of varying subgrade combinations can again be in the sketch. As shown by Fig. 8, a foundation surrounded by soil of a low stiffness will rotate more than one in soil of a higher stiffness. Therefore a small foundation in soil of low stiffness will rotate several times more than a large foundation in stiff soil. The rotation of each individual foundation at one times the ultimate load is given in Table IV for all subgrade. It can be determined from this table what the relation between foundation rotations is for all variations investigated. This is done in Table V where rotations of all foundations are given as a percentage of that of the original foundation size and subgrade.

TABLE IV
ROTATION OF ALL FOUNDATIONS INVESTIGATED AT ONE TIMES THE ULTIMATE LOAD

(Degrees)	SOIL STIFFNESS TYPES			
	HIGH	COMBINATION	ORIGINAL	LOW
4 m	4.46 x10^{-04}	1.46 x10^{-03}	3.01 x10^{-03}	1.15 x10^{-02}
3.5 m	4.77 x10^{-04}	1.56 x10^{-03}	3.66 x10^{-03}	1.50 x10^{-02}
1.75 m	6.37 x10^{-04}	2.23 x10^{-03}	5.44 x10^{-03}	3.49 x10^{-02}

TABLE V
ROTATION OF ALL FOUNDATIONS INVESTIGATED AS A PERCENTAGE OF THE ORIGINAL ROTATION

%	SOIL STIFFNESS TYPES			
	HIGH	COMBINATION	ORIGINAL	LOW
4 m	12.19	39.89	82.24	314.21
3.5 m	13.03	42.62	100	409.84
1.75 m	17.40	60.93	148.63	953.55

C. Changes in Elasticity Modulus and Presence of the Slab

The elasticity modulus used for the slab is in many cases much lower than the prescribed in this case study as designers may, for economical reasons, use concrete of a lower strength than that of structural elements. The elasticity modulus of the slab is reduced for the original subgrade combination and foundation dimensions and the rotations are plotted in Fig. 13.

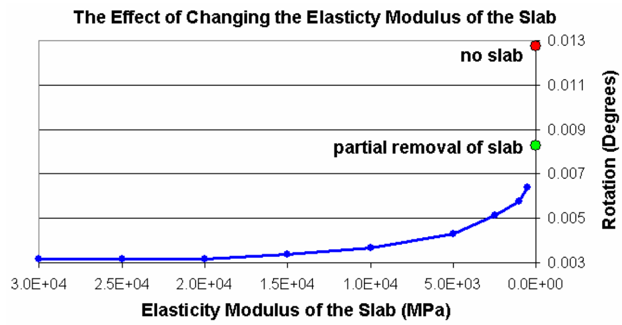


Fig. 13 The effect of total and partial removal of the slab on rotation

Halving the elasticity modulus of the slab only increased the rotation of the foundation by six percent. Using a layer of C3 cemented gravel instead of concrete increased rotation by 160 percent. A further reduction of the elasticity modulus to that of G7 compacted gravel increased rotation twofold. A slab of this type of material does start to become unrealistic as it would not be used in practice. The area of the slab and C3 cemented layer under most stress, that is the associated elements directly adjacent to the column, is investigated by removing these elements from the model. The total absence of a slab and C3 cemented layer is also considered. These results are included in Fig. 13. The complete absence of the slab and C3 cemented layer causes rotations four times higher than the original model. The partial removal results in a 260 percent increase. This large increase of the latter is because of the resistance the slab gives against the overturning column. By removing this part of the slab, greater column rotation leads to higher levels of foundation rotation. The same tests are done for the other subgrade combinations. The same behavior described above is found for the all subgrade combinations (see Fig. 14). An initial decrease in stiffness of the slab does not effect the rotation of the slab. Halving the elasticity modulus of the slab influences the rotation by a fraction. Slabs of lower stiffness are not commonly used in practice. It can therefore be concluded that by using a concrete of a lower grade will not drastically increase rotation of the foundation. The absence of the concrete material or slab entirely could however cause structural instability as large increases in rotation are found.

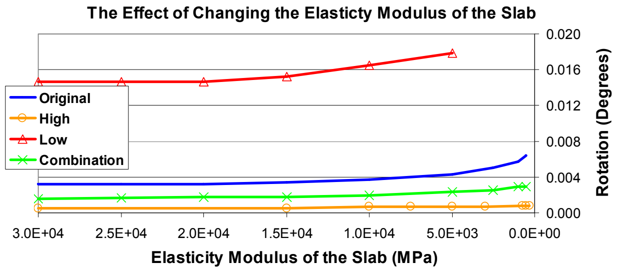


Fig. 14 The effect of changing the elasticity modulus of the slab for various subgrades

D. The Presence of Expansion Joints

The presence of relatively small gaps at the base of the column to allow for expansion joints, commonly used in the industry, have the potential to significantly effect the rotation of the foundation. These joints are filled with material of relatively low stiffness which can effectively be considered as zero. This would mean that should the filler material be compressed, its thickness would deform from typically ten millimeters, to zero; its presence can be ignored and only a physical gap between column and slab need be included in investigations to study its effect. In a worst case scenario, an infinitely stiff column-foundation element, allowing no bending or local deformations will result in a maximum rotation and therefore lateral displacement at the top of the column. This displacement would be in addition to that caused by the deformations due to loading. As an infinitely stiff column-foundation element is neither likely nor possible, a rubber is included in the finite element model and its presence is investigated. The material and geometrical properties are given in Table VI.

TABLE VI
MATERIAL AND GEOMETRICAL PROPERTIES OF THE JOINT FILLER MATERIAL

Elasticity Modulus	Normal Modulus (k_n)	Shear Modulus (k_s)	Bond strength	Thickness
0.5 GPa	50 N/mm^3	5 N/mm^3	0.01 N/mm^2	10 mm

These values indicated a much lower stiffness for the filler material than that of the interface or slab materials. There is no significant difference found in the rotation of the foundation over increasing increments of the ultimate wind load when the expansion joint is included in the design (see Fig.15). The same is found for the subgrade of a higher stiffness and the combination alternative.

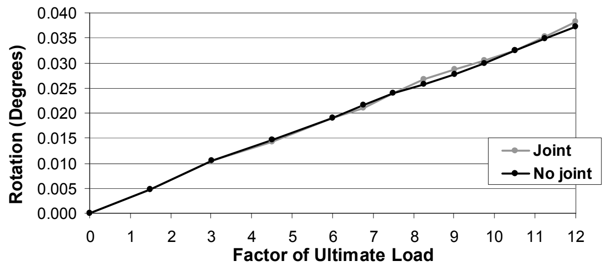


Fig. 15 Rotation versus the factor of ultimate load for the inclusion of an expansion joint

It can be concluded that for the given column-foundation material properties, an expansion joint of 10 millimeter thickness will not cause any note-worthy increase in foundation rotation. This is due to the column not being infinitely stiff; instead the column rotation increases locally (see Fig. 16). With the remainder of the slab still present in addition to the whole C3 cemented layer there is ample resistance to prevent further overturning of the column. The addition of a 10 millimeter rubber around the column will therefore not affect structural stability unless the conditions start to approach those of a worst-case scenario.

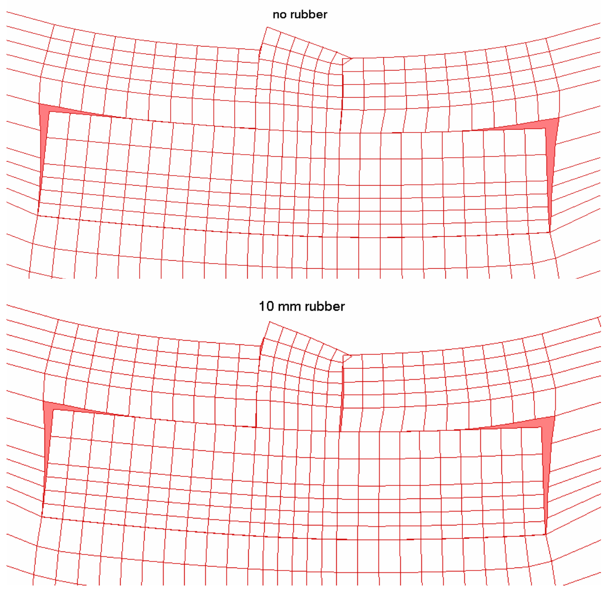


Fig. 16 The delamination of the interface at a magnification factor of 500 with and without rubbers

E. The Effect of Connection Joints

In structures with large floor spans, as in the case of industrial buildings, the slab is made up of smaller segments which are practically possible to build, but also allow expansion/shrinkage movement. These units are connected at movement joints by metal joints or other forms of shear interlocking which are meant to transfer stresses from one to another (see Fig. 17).

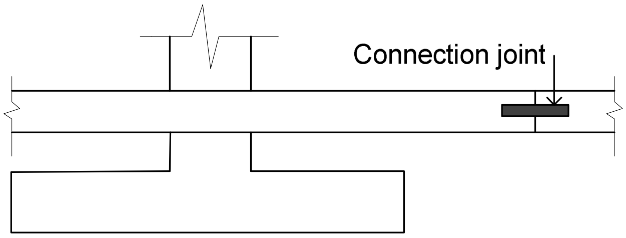


Fig. 17 Structural connection joint used to combine segments of the slab

The event of failure of the connection joints to transfer stresses or hold the slab in place is investigated in this section. To simulate this phenomenon, the boundary conditions of both edges slab of the slab were released and the slab set free to move in all directions without translational constraint. It is therefore assumed that such joints are located far from areas experiencing compression or rotation while the structure is under ultimate loading. The original foundation and subgrade combination is used in this investigation. The ability of the slab to move freely at the edges can be seen in the deformed view of the model in Fig. 18.

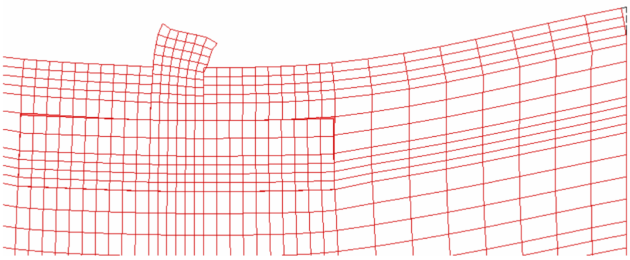


Fig. 18 A deformed view of the free ended slab for ultimate limit loading at a magnification factor of 500

Although the slab edges are free from constraints and the connection joints had therefore failed, there is no increase found for the rotation of the foundation. It is concluded that if connection joints are positioned in non-critical areas, their failure will not affect structural stability.

F. Conclusions

It can be concluded from the investigations carried out in this chapter that several factors can greatly influence the behavior of the structure whereas others do not at all.

As expected, subgrade materials of a higher stiffness offer more resistance to the displacements of foundations than materials of a lower stiffness. This means that higher levels of rotation will occur in a subgrade comprised of clay than would have in compacted or cemented gravel. Changing the size of the foundation has the same effect on the behavior of the foundation where a small foundation rotates more than a large one under the same loading. Combining these factors gives a whole range of behaviors. An example is that a small foundation of 1.75 meters with a thin layer of C3 cemented gravel directly beneath it rotates about the same as a large four meter foundation would without the presence of a stiff layer of subgrade material beneath it. Another example is that for the same loading a small foundation embedded in clay will rotate eighty times more than a large foundation surrounded by C3 compacted material.

The grade of concrete used for the slab need not be a high standard to prevent rotation but a slab must however be present to offer resistance to the overturning of the column. A concrete strength sufficient to carry this compression should be used.

Neither the use of expansion joints in close vicinity of the column nor movement joints to allow free movement of slab segments will cause a significant increase of the rotation of the foundation, provided they are used sensibly.

VII. Conclusions and Recommendations

It is concluded from investigations carried out that some factors can greatly influence the behavior of the structure and others do not.

Variations in the stiffness of the subgrade materials and the size of the foundation can have significant impacts on the foundation response to ultimate loading. Less rotation occurs in subgrade materials of a higher stiffness than in materials of a lower stiffness. Increasing the size of the foundation has the same effect on the behavior of the foundation. A large foundation rotates less than a small one under the same loading. Combining these factors gives the user a range of alternatives to ensure structural stability. The user might find that designing a larger foundation will offer sufficient stability and expensive soil-works and compactions will not be necessary to prevent rotations. The user might also find that a smaller foundation is adequate for his/her current subgrade compilation.

Realistically lower grades of concrete for the slab will not noticeably effect the rotation of the foundation, but a slab must be present to prevent overturning of the column. The user must take note of the forces acting on the column at the level of the slab. If crushing of the column or slab may occur at this level it is the responsibility of the designers to take adequate action to prevent this phenomenon.

The sensible use of expansion joints in close vicinity of the column or movement joints to allow free movement of slab segments, will not cause a significant increase of the rotation of the foundation. The user should however confirm the design of these joints if they differ significantly from those investigated in this study. In addition, as stated in chapter one, it is also the responsibility of the designer to prevent the uplifting of the foundation under wind loads, provided sufficient shearing capacity to prevent the forming of hinges in the structure, and to be sure that the foundation is stable against toppling over.

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