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Foundation Structures for Tall Buildings

Structures des fondations pour les maisons hautes

Fundationen für Hochhäuser

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1. FOREWORD

A foundation must transmit the load of a structure to the underlying soil or rock safely and without excessive settlement. Decisions in design of all foundations must always be made with this object in view. To achieve the object the following design principles are stipulated in the Structural Standards for Building Foundations of the Architectural Institute of Japan, which is a nation-wide organization of building engineers and architects:

i) The foundation should be supported by a strong, stable soil stratum or rock; the support by incompetent soils should be avoided.

ii) The foundation of a building should not be supported by different soil strata with noticeably different characteristics.

iii) A building should not be supported by foundations of different types.

iv) The stresses induced in the soil at the foundation base should be distributed as uniformly as possible throughout the plan of a building, and should afford a sufficient margin for safety against failure of the supporting soil strata as well as development of excessive settlement.

v) The bases of columns should be tied with foundation beams of sufficient stiffness so that the entire foundation forms a rigid grid to act as a unit.

Even though this paper is concerned with the foundation design for tall buildings, one needs hardly add anything to these general principles. However, because of characteristics peculiar to the structural systems and loading conditions of tall buildings, a number of problems may be pointed out which require special considerations. In relation to the foundation of a tall building, such problems will briefly be summarized and discussed in the following sections from three major standpoints:

1. Static weights
2. Wind forces
3. Seismic forces

2. STATIC WEIGHTS

Tall buildings are characterized, first of all, by their large weights far heavier than usual, low to medium-rise buildings. The fact frequently imposes rigorous problems on the design of foundations in various aspects.

AVERAGE WEIGHT - In Fig.1, average weights (dead plus design live loads excluding weight of foundation) are shown in metric tons per

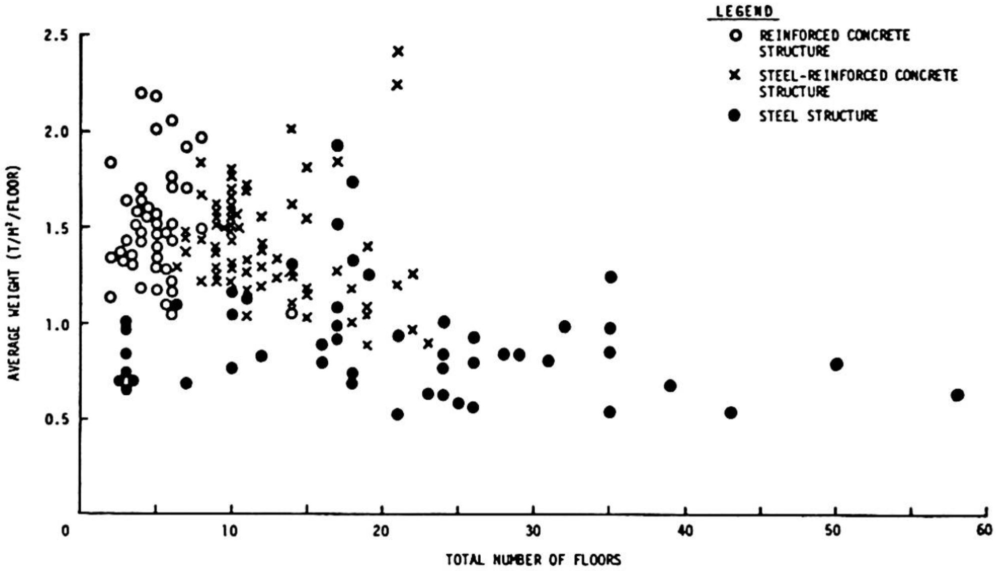

Fig.1

unit area per one floor with respect to typical Japanese buildings of different structural types. In spite of the wide range of values for low to medium-rise buildings, it may be seen for tall buildings that the values nearly tend to converge and may likely be between 0.5 and 0.8 tons/sq.meter/floor. In this connection, it is a common practice to accommodate a tall building with the basement of reinforced concrete or steel-reinforced concrete whatever the structural material of the superstructure may be. Unit weight of the basement alone is approximately equal to 1.75 tons/sq.meter/basement floor on the average.

In Fig.2, average weights of foundations (footing, mat, foundation beam, excluding weight of piles or piers) are also shown in terms of the total number of floors of a building, indicating that the values are in the range from 0.12 to 0.17 tons/sq.meter/floor for typical, tall buildings.

Hence, the estimate of the total average weight of a tall building including foundation may probably be in the range of 0.6 to 1.0 tons/sq.meter/floor. Although little information is available to the author concerning the weights of tall buildings in foreign countries, they may likely be of no significant difference from the above rough estimate.

BEARING CAPACITY - Fortunately, almost all major cities in this country are underlain by firm and stiff sandy or gravelly strata of sufficient thickness, which geologically belong to Diluvial deposits and can be encountered from the ground surface within a depth from 10 to 30 meters. Therefore, all of tall buildings designed so far are supported by those strata using either a spread foundation or a pier foundation of rather short length, being able to comply with Item i) in the aforementioned design principles. Up to the present time, no tall building has been constructed with long, flexible pile foundation.

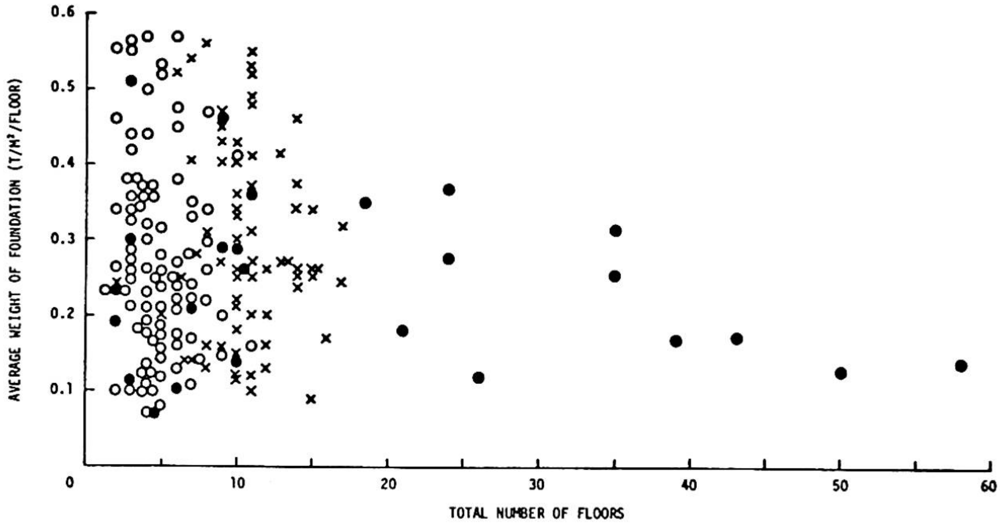

Fig.2

In practice, the ultimate bearing capacity of soil is estimated on the basis of Terzaghi's bearing capacity formula (Terzaghi 1951)

$$q_{ult} = \alpha c N_c + \beta \gamma B N_\gamma + \gamma D_f N_q \tag{1}$$

where

q_{ult} : ultimate bearing capacity
c : cohesion of soil
γ : unit weight of soil
α, β : shape factor
N_c, N_q, N_γ : bearing capacity factor
D_f : depth of embedment
B : width of foundation

The ultimate bearing capacity thus calculated at the design stage is usually verified by performing a field plate-loading test before or during construction. In Fig.3, a hatched zone is shown which represents the range of bearing pressure vs. settlement curves in the field plate-loading tests for sand and gravel strata supporting tall buildings. These tests are ordinarily performed by using a small loading plate 30 by 30 or 45 by 45 centimeters square. The majority of the loading tests give results in reasonable accord with those estimated by eq.(1). Furthermore, in cases where actual tall buildings provided with mat foundations of large dimensions and the basement of considerable depth are involved, real bearing capacity may probably be much larger than are shown in Fig.3 because of the effects of large width

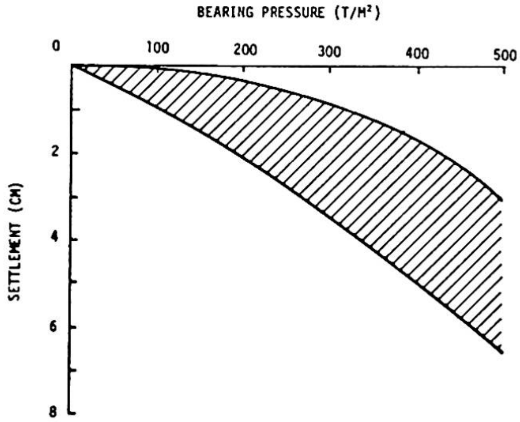

Fig.3

and deep embedment, which are accounted for by parameters B and D_f in the second and third terms of eq.(1), respectively.

When a pier foundation is used beneath the base level of a tall building, the bearing pressure at the bottom of a pier sometimes approaches to about 400 tons/sq.meter in our recent experience. In such a case, the full-size loading test of a pier is usually required and, so far, the safety of the bearing soil strata has been verified to be still sufficient. In some cases, for the purpose of estimating the ultimate bearing capacity at the design stage, Meyerhof's formula (Meyerhof 1950) is utilized, which is known to be pertinent for a deep foundation allowing larger bearing capacity factors than those in eq.(1). However, the compatibility of this analytical approach with the field loading test results does not seem to be completely established yet.

If the bearing pressure comes to an extremely high magnitude, the safety of foundation must be ensured not only against the sliding failure, which is primarily governed by shearing strength of the soil and analytically represented by Terzaghi's or Meyerhof's formula, but also against the so-called crushing failure which is related to crushing strength of individual soil grains themselves. Judging from a few test results performed so far, the ultimate bearing capacity resulting from crushing failure seems to be approximately

1800	tons/sq.meter	for sandy gravel
2000	"	for cemented sand.

In consideration of the aforementioned average weight of tall buildings, these knowledge and experience may provide a basis for stating that there is no practical limitation of the height of a building from the geotechnical standpoint, provided that competent materials with bearing characteristics not inferior to those shown in Fig.3 can be encountered within a reasonable depth from the ground surface.

SETTLEMENT - Any building undergoes settlement during construction and, under adverse conditions, may suffer a long-continuing, post-construction settlement caused by consolidation of the underlying cohesive soil deposits.

The former is usually referred to as immediate settlement. The immediate settlement results primarily from elastic compression of the soil mass beneath the loading area and, in addition, is associated with the recompression of rebound or heave taking place as a consequence of stress relief by excavation if the construction of a deep basement is involved.

The elastic settlement may be evaluated on the basis of theoretical analysis of an elastic solid. In the aforementioned A.I.J. Structural Standards, the following formula (Steinbrenner 1934, Fox 1948) is recommended for the evaluation:

$$S_o = \mu_H \mu_D q \sqrt{A}/E \tag{2}$$

where

S_o : elastic settlement
q : average loading intensity
A : contact area of foundation
E : modulus of elasticity of soil mass
μ_H, μ_D : settlement factors

With respect to a few tall buildings in the city of Tokyo, the results of computation on the basis of eq.(2) are compared in Table 1 with actually observed elastic settlements, indicating fairly reasonable agreement.

Table 1 : Computed and Observed Elastic Settlements of Tall Buildings

Building	Total Number of Stories	Settlement(cm)	
		Computed	Observed
A	39	2.2	0.8
B	43	1.5	1.5
C	50	1.3	1.5

For the computation in Table 1, moduli of elasticity were estimated on the basis of the load-settlement curves obtained by field plate-loading tests. In addition, in the case of Building C, the average modulus of the supporting soil mass was also measured dynamically by seismic exploration. It is interesting to note that the results of seismic exploration can provide another reasonable determination of static soil modulus if the observed value is pertinently modified by taking into account the strain levels within the stressed soil mass (Seed 1969).

Under the present situation, the analytical procedure to evaluate the settlement of a pier foundation seems not yet successful even as a crude approximation for practical purposes. Therefore, the evaluation is usually made by performing a full-size loading test or on the basis of available, previous data under appropriate conditions similar to the new site.

Differential settlements have entailed no critical consequences so far for tall buildings of a simple shape, probably because of the physical and structural reasons: (1) Since the buildings are designed so as to rest on a firm soil stratum in compliance with Item i) of the design principles, the maximum settlement is already limited to such an extent that no significant differential settlements occur, and (2) the tall buildings essentially possess high, structural stiffness to withstand vertical distortions and it functions, in turn, to minimize the differential settlements by redistribution of the column loads. Particularly, the presence of the basement having thick walls and a rigid foundation grid makes an important contribution in this respect.

An exception is the case shown in Fig.4, i.e., a tall building with structurally united low-rise annex. Large difference in weights of the high-rise and low-rise portions of the building shown in Fig.4(a) will probably result in significant differential settlements. A preventive measure is usually taken in practice in such a way that both portions are first constructed separately and, immediately prior to the completion, they are connected and finished. For a tall building with partial pier foundation as shown in Fig.4(b), which

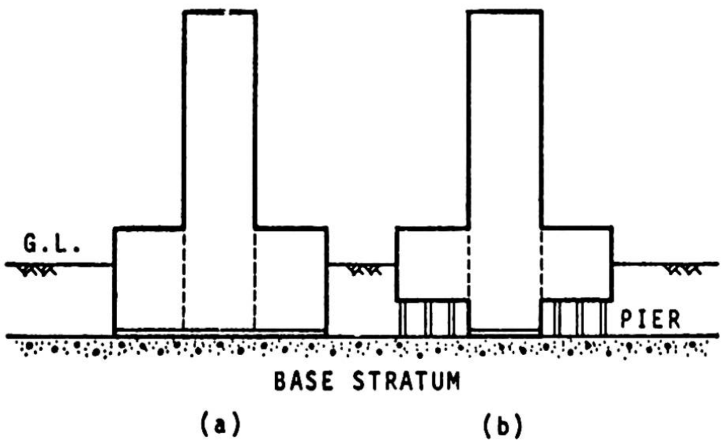

Fig.4

inevitably violates Itam iii) of the design principles, the same process of construction is frequently adopted since, as pointed out previously, much uncertainties are involved in estimating the settlement of a pier foundation.

The rebound at the bottom surface of excavation frequently presents a troublesome problem. Reports from a few building sites (Endo et al 1969) disclosed that the observed rebounds amounted to

32 mm for a 16 meters deep excavation
60 mm for a 25 meters "

The rebound taking place at the bottom of excavation can not be noticed unless special measurements are made. It is required for a precise observation of the rebound to install reference points immediately below the proposed bottom level of excavation and to carefully protect them against damage by excavation works. On the other hand, it appears possible to a certain extent to calculate the approximate amount of rebound by referring to the slope of unloading branch of load-settlement curve obtained by a field plate-loading test, provided that the stratification of underlying soil deposits is not too much complicated.

When there is no noticeable non-uniformity in the distribution of column loads, no special measures are taken in practice even if appreciably large rebound is anticipated. However, for a building with extreme difference in weight distribution, the problem of different recompression is usually solved by providing construction joints as described previously.

The second type of settlement results from consolidation of underlying cohesive soil deposits, which increases continuously even after the completion of a building. In fact, in the majority of cities in our country, the firm bearing stratum is usually underlain by clayey soil deposits. Fortunately, however, they are the sediments in the geological era of old Diluvium and in most cases highly over-consolidated, resulting in no critical consequence from the standpoint of consolidation settlement.

FLOATING FOUNDATION - Where a firm stratum of sufficient load supporting capacity can not be encountered within a reasonable depth from the ground surface as is frequently seen in a city underlain by marine or lacustrine sediments of low strength and high compressibility, an effective way of constructing a building of low to medium height is to use the so-called floating foundation.

The basic concept of floating foundation is that the weight of a building is compensated by the weight of the excavated soil so as to impose no additional loads upon underlying soil deposits as a result of constructing the building. The term of floating foundation may be rather misleading and, in a strict sense, it should be referred to as a compensated foundation (Zeevaert 1972).

Now, referring again to the average weights of tall buildings described previously, assume approximately

average weight of superstructure = 0.65 t/m^2/floor
average weight of basement = 1.75 t/m^2/floor
average weight of foundation = 0.15 t/m^2/floor
unit weight of soil mass = 1.50 t/m^3
average story height of the basement = 4.00 m

and let

N : total number of floors
N_B : total number of floors in the basement

W : total weight of the building per unit area

W_e : total weight of the excavated soil mass per unit area,

then

$$W = 0.65 \times (N - N_B) + 1.75 \times N_B + 0.15 \times N \quad (3)$$

$$W_e = 1.50 \times 4.00 \times N_B \quad (4)$$

To establish full compensation, eqs.(3) and (4) must be equated:

$$W = W_e \quad (5)$$

From eqs.(3), (4), and (5), one obtains

$$N_B \simeq 0.16N \quad (6)$$

and Table 2 shows a few numerical solutions of eq.(6). The above computation is merely a very crude arithmetic; nevertheless, eq. (6) or Table 2 implies that the application of the concept of fully compensated foundation may practically be precluded for a tall building of more than approximately 40 stories.

Table 2 : Required Depth of Basement for Fully Compensated Foundations

Total Number of Floors	20	30	40	100
Required Number of Basement Floors	3	5	6	16

3. WIND FORCES

Winds acting on tall buildings develop large temporary loading which must be delivered ultimately to the soil through the foundation or the basement walls. Shear force and overturning moment resulting from wind loads at the foundation level of a tall building are both characterized by their extremely large magnitude. Judging from experience of designing tall buildings up to the present time, wind forces and wind moment at the foundation level become larger for a typical building of more than 50 to 60 stories than those resulting from earthquakes even in this country of extremely high seismicity.

As a tall building is usually accommodated with the basement of a considerable depth, the large shear force is resisted by the difference of earth pressures acting on leeward and windward faces of the basement as well as the frictional forces of surrounding soils along its side and bottom faces. If a building is supported on pile or pier foundation, the lateral resistance at the top of the piles or piers contributes as well to withstanding the shear force. If this is the case, however, little benefit of frictional resistance along the bottom face of foundation may be expected because of loose contact of the soil or separation resulting from ground subsidence.

In practical analyses, the resistances by Rankine's pressure and shearing strength of the soil, acting on each corresponding face of the basement, are usually taken into consideration. As to the lateral resistance of piles or piers, the beam-on-elastic-foundation method or its extension to plastic range are frequently referred to. As is well known, however, the deformations required for full mobilization of these resistances are not necessarily the same and, moreover, may likely exceed the acceptable limit of movement. It is an important but difficult question at the present time to calculate the contribution of each resisting component compatible with the tolerable displacement, because so many complex factors are involved (DeSimone 1972).

The overturning moment causes an increase of bearing pressure or pile load on the leeward side and a decrease on the other side of the foundation; the former must be withstood by bearing capacity of the soil with an adequate margin for safety. If the overturning moment becomes still larger and the decrease of bearing pressure at the windward edge of the foundation exceeds the static pressure, the problem of uplift is encountered, which is an important matter peculiar to a tall building. The occurrence of uplift may be interpreted as the commencement of a transient motion from stable to unstable state of a structure, it can not be overlooked and should be avoided if possible.

To illustrate the possibility of uplift by wind loading, now assume a simple, prismatic model of a building as shown in Fig.5. The model is assumed to be directly placed on the ground surface. The total height is assumed equal to 3.5N meters, where N is the total number of stories and the average story height of 3.5 meters may be used without introducing much error. If 0.65 tons/sq.meter /floor is again assumed as the average unit weight of tall buildings, it is apparent that the bearing pressure of the supporting soil is equal to

$$\sigma_{static} = 0.65N \quad t/m^2 \qquad (7)$$

under static, permanent loading.

Then, consider the building is subjected to wind pressure; the wind pressure coefficient C = 1.2 and the wind pressure distribution $q = 0.12x^{1/4}$ (t/m^2) at the height of x meters are assumed, which may probably be an acceptable assumption for the purpose of approximate computation. Under these loading conditions, the overturning moment becomes

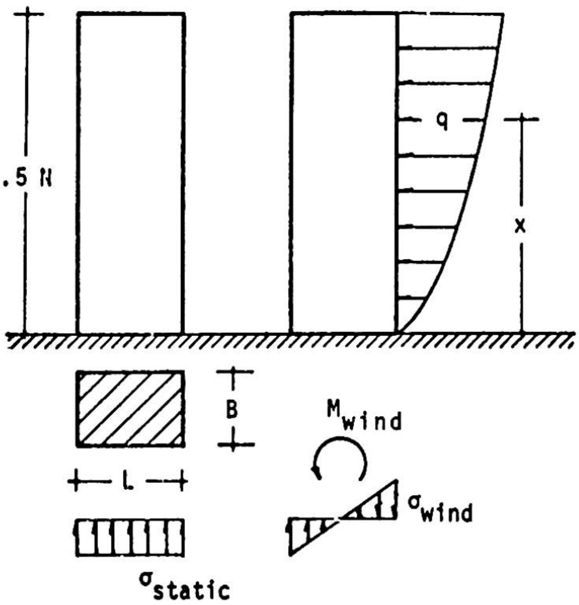

Fig.5

$$M_{wind} = \int_0^{3.5N} Cq\cdot Bdx = 1.072BN^{9/4} \quad t\cdot m \qquad (8)$$

and the maximum bearing pressure is represented by

$$\sigma_{wind} = (6/BL^2)\cdot M_{wind} \qquad (9)$$

Obviously, the condition to cause no uplift is $\sigma_{wind} \leqq \sigma_{static}$. From these equations, the minimum side length required for preventing the initiation of uplift may approximately be expressed by

$$L_{min} = 3N^{5/8} \qquad (10)$$

or as shown numerically in Table 3.

Table 3 : Minimum Side Length for Preventing Uplift

Total Number of Stories, N	20	40	60	90	120	200
Minimum Length, L, in Meters	20	30	40	50	60	80

In this connection, it may not be useless to pay attention to the behavior of foundation after the uplift has once taken place. Now, consider a loading plate as shown in Fig.6(a). The plate is also assumed resting on linear springs, which represent the subgrade reaction of the supporting soil and can not develop any tensile reaction. Then, corresponding to the combined effect of P and M, three different stress patterns can be distinguished; (b) no uplift, (c) on the verge of uplift, and (d) partial uplift. Obviously, under the action of constant, vertical load, the stress state transfers from (b) to (d) through transition point (c) as the moment gradually increases. The relationship between the moment and the angle of rotation can be expressed by

$$\left.\begin{array}{lll} M^* = \theta^* & \theta^* \leqq 1 & \text{for state (b)} \\ M^* = 3 - 2/\sqrt{\theta^*} & \theta^* \geqq 1 & \text{for state (d)} \end{array}\right\} \qquad (11)$$

where

$$M^* = M/(PL/6)\,,\quad \theta^* = \theta/(2P/kL^2)\,.$$

The rotational characteristics of the loading plate expressed by eq.(11) are shown in Fig.7. It will be seen in Fig.7 that the behavior of foundation develops non-linearity if the moment exceeds a limit

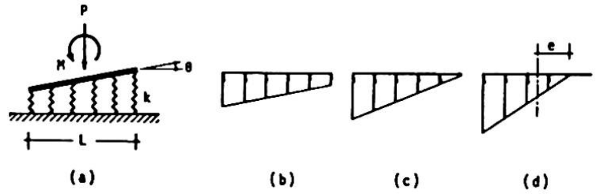

Fig.6

$$M_{limit} = PL/6 \qquad (12)$$

which is a counterpart of eq.(10) for a tall building subjected to wind loading.

Such non-linearity should be referred to as geometrical non-linearity to distinguish it from the one developed by plastic properties of the soil itself.

No serious problem of uplift has been actually encountered so far in the design of tall buildings, since it can readily be overcome by extending the lower portion and setting back the upper portion of the building or by providing adequately deep basement. However, careful attention should be paid to such a building of urban location where little space is allowed between the building and the property lines.

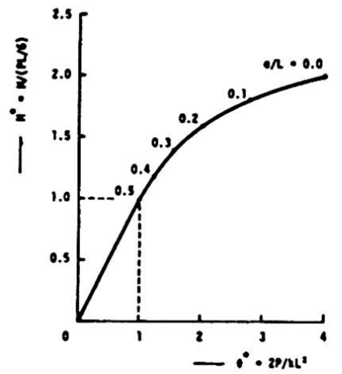

Fig.7

The behavior of a basement in delivering shear force and overturning moment to the surrounding soil is another difficult problem to be dealt with analytically. A proposal (Ohsaki 1973) is presented on the basis of the theory of elastic halfspace, but it is primarily of theoretical interest and difficult to apply to design purposes. Three-dimensional finite element approach to the problem appears to be useful and, in fact, is utilized frequently in practical design. However, it requires considerable judgment and experience for selecting representative values of soil parameters which should be taken into the analyses and, in addition, the agreement between calculated and actual behaviors has not yet satisfactorily been verified.

4. SEISMIC FORCES

As has been pointed out previously, the major concern in designing the foundation of tall buildings lies in the effects of wind forces rather than seismic forces under the majority of situations; nevertheless, the dynamic effects of an earthquake must still be of great interest to the building engineers, since they might affect the design of not only the foundation but the overall structure to a considerable extent.

Usually, the influences of the foundation and the underlying soil deposit upon a building are discussed by dividing them into three categories:

(1) soil amplification, which implies that the stiffness and thickness of entire soil strata affect the motion at the surface of the soil,

(2) dynamic soil-structure interaction, which represents the combined effects on the ground motion of the presence of a building and the deformation and energy-dissipation characteristics of the soil immediately beneath the building, and

(3) resonance, which may take place between the building and the ground motion thus developed, resulting in high stresses and large distortions in the building.

The foundations of tall buildings are carried down through soft soils to a stiff soil stratum or rock from necessity for bearing heavy weight. First, this fact may likely minimize disadvantageous effects of soil amplification, whether the building is directly rested on the bearing stratum by the spread foundation or it is supported on the pier foundation. A number of reports are available indicating that the difference between the response spectra of the earthquake motions observed at the base of buildings and those observed at the level of the bearing strata is hardly noticeable with buildings supported on piers of high stiffness (Ohsaki 1969). A case where a tall building is still associated with the large earthquake motion as a result of soil amplification is that the support of long, flexible piles is involved. It is also reported frequently that the characteristics of response spectra of the earthquake motions at the base of pile-supported buildings exhibit a tendency to resemble those which would be observed at the ground surface of the same site (Ohsaki 1969). It is extremely probable that piles of large flexibility develop the same movement with the amplified motion of the surrounding soil deposit.

Secondly, for a building with the foundation carried down to a stiff bearing stratum, the effects of soil-structure interaction are of minor significance from the practical viewpoint. The interaction induces rocking and swaying motions to a building and, as a result, shifts the fundamental period of the building toward the longer side. Numerically, however, its effect on buildings up to 40 stories high is not likely to exceed 4 percent if the shear wave velocity for the underlying soil is approximately 500 meters/sec (Whitman 1972). Furthermore, the response spectrum of input acceleration has in general a downward slope in the range of fundamental periods of tall buildings and, consequently, interaction always acts beneficially to reduce the stresses in structural elements in a tall building.

Thus, the dynamic design of a tall building subjected to seismic forces is almost solely related to characteristics of the motion of the stiff bearing material itself, which have been considered to rarely involve harmful components to tall, flexible buildings.

In recent years, however, a new finding is being frequently pointed out that even the seismic motions of rock or rock-like hard stratum involve the wave components of extremely long periods, which might have considerable damage-potential to a tall building on account of the resonance. Fig.8 represents two examples of velocity spectra for such rock motions during earthquakes of considerably short, epicentral distance. This fact of long-period inclusion is also observable in a large number of microtremor records obtained at the outcrops of rock or at the deep-seated hard strata, while the true character of such wave components has not yet been unmasked from the seismological standpoint. It might possibly be of

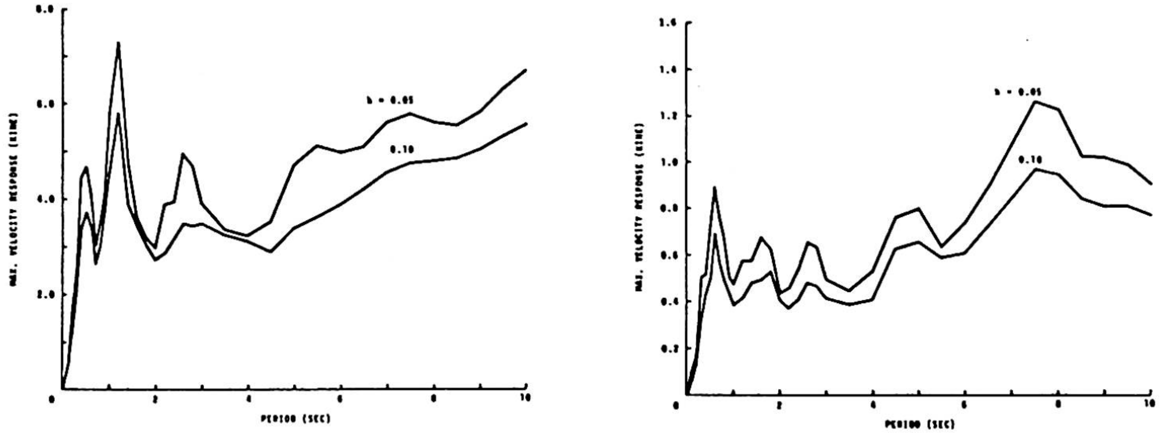

Fig.8

no little significance since, so far, such nature of input earthquake motions has seldom been taken into consideration as a basis of designing tall buildings.

5. CONCLUSION

A foundation in general must transmit any load of a structure eventually to the underlying soil or rock safely and without excessive settlement. Decision must always be made with this object in view for the foundation of a tall building as well.

However, because of characteristics peculiar to the structural systems and loading conditions of tall buildings, a number of problems are encountered which require special considerations.

Tall buildings are characterized, first of all, by their extremely heavy weights, and this fact frequently imposes rigorous problems on the design of foundations in various aspects. The average weight of tall buildings is estimated statistically to be in the range of 0.6 to 1.0 tons/sq.meter/floor.

Where a strong, stable stratum can be encountered within a reasonable depth from the ground surface, the ultimate bearing capacity and differential settlements usually give no critical consequence in spite of the heavy weight of tall buildings. To the differential settlements resulting from the large difference in distribution of loading intensity and the rebound of the bottom of excavation, attention should be paid however. Where the site is underlain by deep sediments of soft soils, the concept of floating foundation may hardly be applicable to a tall building, although it is quite effective for a building of lower height.

The foundation of a tall building is subjected to large lateral force and overturning moment during high winds. Behaviors of the foundation and the basement walls in transmitting these loads to the surrounding soils are considerably difficult to deal with analytically, being sometimes associated with another problem of uplift.

Seismic forces affect the design of foundations in a number of ways such as soil amplification, dynamic soil-structure interaction and resonance. If, however, the foundation is carried down through soft soils to a stiff bearing stratum, the disadvantageous effects of amplification and interaction are of minor significance, except in the case where a long, flexible pile foundation is involved. A finding that even the seismic motions of rock involve the wave components of extremely long period may be of no little significance for the design of tall buildings, requiring further studies.

In this Introductory Report, presentations are mostly made in general terms and it is not intended to discuss any specific problem in detail. A few simple, numerical examples are presented, but they are only for illustrative purposes.

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SUMMARY

In this introductory Report, a number of problems related to the design of foundations of tall buildings are briefly summarized and discussed primarily from the standpoints of static weights, wind forces and seismic forces with a few illustrative, numerical examples.

RESUME

Ce rapport introductif présente un résumé sur les problèmes concernant le dimensionnement des fondations pour maisons hautes; ils sont examinés essentiellement en vue des charges statiques, du vent et des effets sismiques. Quelques exemples sont présentés.

ZUSAMMENFASSUNG

Der vorliegende Einführungsbericht behandelt eine Anzahl von Problemen, welche sich beim Entwurf von Hochhaus-Fundamenten stellen. Die Probleme werden kurz zusammengefasst und vor allem im Hinblick auf statischen Lasten, Windkräfte und Erdbebeneinwirkung an Zahlenbeispielen diskutiert.