An analysis on allowable settlements of structures

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ABSTRACT: This paper examines allowable settlements of structures built in Italy, the results of which have been published in the last 25 years.
Sixty-nine structures of various types with both superficial and deep foundations in cohesive, granular and layered soils are analysed.
After a brief state-of-the-art of the various methods used to approach the problem, various cases are examined with reference to the models proposed by Skempton and MacDonald.
The good correlation between maximum settlement and angular distorsion allowed preliminary elements for an evaluation of admissible deformations on the basis of settlement calculations.

1. Introduction

The observation of the settlement of structures and possible consequent damage is undoubtedly a valid method of evaluating the limits within which certain types of structure may accept deformations without weaknesses which may jeopardize or restrict their use.

The principal disadvantages of this method of investigation are the subjectivity of damage evaluation and the difficulty of assessing which limits influence possible defects or construction typologies rather than the extent of settlement in a particular damaged structure.

Undoubtedly, the conclusions which may be drawn from a set of data must be formulated with great caution, due to the fact that the problem of the soil/structure interaction is extremely complex and influenced by a high number of parameters.

However, at least as far as the field of values is concerned, investigations on real-size models certainly supply valid results, especially if a high number of observations are made.

This study forms part of this approach and aims at extending knowledge on known cases by means of an analysis on Italian structures, details of which have been published in the literature.

2. Aims of this study

Load application during building modifies the tensional conditions initially present in the subsoil and causes a state of deformation, whose sum on the surface, measured vertically, is called « settlement ».

Settlements occurring during the life of the structure (i.e., during and after its construction) are « admissible » when they are tolerated by its architectural, static and planning elements. However, other factors may intervene in defining the criterion on which allowable settlement is based, such as aesthetic, psychological, legal and economic factors. The presence of cracks in the plasterwork of a house may be hardly significant from the structural viewpoint, but it may be of great importance from the aesthetic, psychological and economic viewpoints and may affect its price per square meter.

TOMLINSON, DRISCOLL and BURLAND [1978] have attempted to define visible damage in walls by correlating them with the degree of difficulty required to repair them. They defined five categories of damage, ranging from opening of cracks in wall coatings and walls between 0.1 mm and more than 25 mm.

International bibliographies show that many authors have considered the problem of settlement admissibility and have proposed various original approaches.

In many cases, the type of superstructures, foundation and soil were examined. In date order, important conceptual contributions have been supplied by MEYERHOF [1947, 1953], SKEMPTON and MACDONALD [1956], POLSHIN and TOKAR [1957], BJERRUM [1963], BURLAND and WROTH [1974] and BURLAND, BROMS and DE MELLO [1977]. Some authors have also confirmed, extended or limited, and generalized the above studies, sometimes amplifying existing case histories. Of these, GRANT *et al.* [1974] substantially confirmed the studies of Skempton and MacDonald, while WAHLS [1981] generalized the approach of Skempton and Mac Donald, homogeneizing it with the theories of Polshin, Tokar and Burland.

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Studies on the behaviour of real structures, often taken from the literature, are of great importance, since they supply data allowing verification of concepts and theories proposed.

The aim of this work is to insert Italian cases, obtained from archive data and published studies, into the context of the above-quoted experience, with the aim of evaluating aspects showing analogies, possible discrepancies, or original and significant features.

3. Definitions and synthesis of main historical developments

Various methods have been proposed for quantifying the extent and type of settlement. Each method requires the definition of characteristic terms necessary in order to develop the problem.

It is therefore necessary, when synthetizing these researches, to find common definitions for the main terms used.

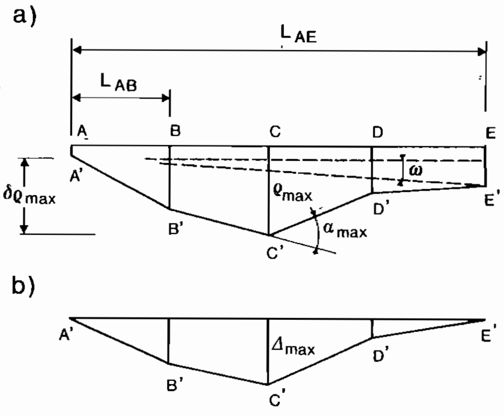

Fig. 1. - Reference situation utilized to define settlement terms.

Fig. 1. - *Definizioni di cedimento.*

Referring to Fig. 1, showing 5 points ranging from an original position (A-E) to a translated position (A'-E'), we may define the following terms:

— *settlement* ρ: vertical movement downwards of a particular point. Maximum settlement ρ_{max} refers to point C(ρ_C);

— *differential settlement* $\delta\rho$: difference between settlement of any two points. Maximum differential settlement refers to point A and C: $\delta\rho_{max} = \rho_{max} - \rho_{min} = \delta\rho_{CA}$;

— *rotation* ω: rigid movement of the whole structure. This is a concept usually applied to continuous foundations. In the case shown in Fig. 1, $\omega = \arctan(\delta\rho_{AE}/L_{AE})$. The term «tilt» is sometimes used;

— *slope* a gradient between two successive points defined as $\delta\rho_{MN}/L_{MN}$, the term introduced by POLSHIN and TOKAR [1957]. The term *angular distorsion* is often used [SKEMPTON and MACDONALD, 1956; BJERRUM, 1953]. If necessary, the effect due to rotation is subtracted from the *slope*;

— *relative deflection* Δ: maximum movement from a straight line joining two reference points (see Fig. 1b);

— *curvature*: Δ/L (also called *deflexion ratio*): this is the ratio between relative deflexion and the reference stretch examined. The term curvature of the deflection curve was initially proposed by HORN and LAMBE [1963]; the deflexion ratio was proposed by POLSHIN and TOKAR [1957] and used by BURLAND and WROTH [1974].

The total deformation of a foundation or structure may be subdivided into several parts, separating the various factors contributing to « settlement » according to the above concepts.

For example, Fig. 2 shows that total movement may be subdivided into the sum of uniform settlement, rotation, and curvature. It should be noted how the concepts « curvature » and « slope » are linked.

It is generally agreed that uniform settlement is not responsible for damage to the superstructure, although strong settlements ($\rho >$ > 150 mm) may cause weakness in facility connection (drains, gas pipelines, etc.). The rigid rotation of a structure is often not tolerated when it may be seen. In high buildings, this may occur with rotation of about 1/250 [BJERRUM, 1963], although many authors do not consider that rigid rotation is responsible for structural damage. This view is under di-

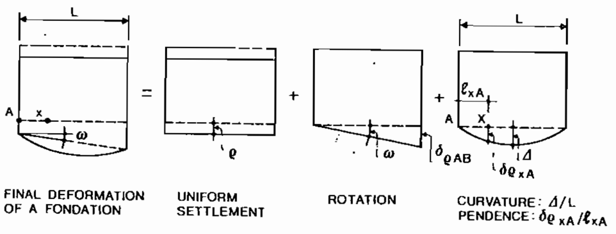

Fig. 2. - Various components of « settlement ».

Fig. 2. - *Varie componenti del « cedimento ».*

scussion, due to the fact that rotation may be associated with redistribution of stresses acting on the foundation plane, with possible repercussions on the superstructure, especially for framed structures founded on isolated plinths [Leonards, 1975]. Research-workers generally agree that criteria based on maximum slope (i.e., on maximum angular distorsion) and maximum curvature (i.e., maximum ratio of deflexion) are the most important when analysing the admissibility of movements in relation to superstructure problems.

Referring to angular distorsion, on the basis of their data from 98 civil and industrial buildings, Skempton and MacDonald suggest the characteristic limits shown in Table I.

A particularly extensive experimental study was conducted by Bozozuk [1962] on 574 civil monotype buildings in Ottawa (Canada). These buildings were all two-and-a-half storeys high, built in veneer brick load-bearing walls with superficial foundations. Sixty to eighty years after building their state of damage (when present) was observed. Settlement was mainly due to soil drying. The main results of this study are summarized in Table II.

This type of approach, already criticized by Terzaghi [1956] and which, according to Feld [1965], is difficult to generalize, was not only maintained but even developed by Bjerrum [1963] and Grant *et al.* [1974] and by many contributions by Meyerhof [1953, 1977, 1979].

Table III shows the characteristic admissible and danger limits proposed by Bjerrum and Meyerhof. However, these values must not be considered rigid design rules, but rather as indications for useful comparisons, seeing that « each building or structure should be treated on its own merits, for its performance will depend on a large number of factors including construction materials, method and form of construction, type of cladding and brittleness of finishes » [Burland, 1977].

Other limits have been proposed using the parameter of curvature Δ/L (or deflexion ratio). In this case, referring to load-bearing brick walls, Polshin and Tokar took into account structural stiffness on the basis of wall sizing and type of building.

Meyerhof pointed out that the geometry of the deformation of walls is fundamental to the problem of the soil/structure interaction.

Relative positive deflexion (as in stretch A′-D′ in Fig. 1) are less dangerous than negative ones (C′-E′: Fig. 1).

Table I

Angular distorsion	Characteristic situation
1/300	Cracking of the panels in frame buildings of the traditional type, or of the walls in load-bearing wall buildings;
1/150	Structural damage to the stanchions and beams;
1/500	Design limit to avoid cracking;
1/1000	Design limit to avoid any settlement damage.

Table II

Settlement (cm)	Slope	Damage
a) less than 5	1/180	No damage
b) $5 < \rho > 10$	1/120	Slight
c) $10 < \rho > 15$	1/90	Moderate
d) more than 15	1/50	Heavy and (e) severe

Table III

Angular distorsion (Slope)	Damage or allowable criteria
1/750	Limit where difficulties with machinery sensitive to settlement are to be feared
1/600	Limit of danger for frames with diagonals
1/500	Safe limit for buildings where cracking is not permissible (safe limit for reinforced load-bearing walls)
1/300	Limit where first cracking in panel walls is to be expected; limit where difficulties with overhead cranes are to be expected
1/250	Limit where tilting of high, rigid buildings might become visible (danger limit for panel walls of frame buildings and reinforced load-bearing walls; safe limit for open steel storage tanks and tilt of high rigid strutures)
1/150	Considerable cracking in panel walls and brick walls; safe limit for flexible brick walls, with h/L 1/4); limit where structural damage of general buildings is to be feared (danger limit for open steel and reinforced concrete frames, steel storage tanks and tilt of high rigid structures; safe limit for statically determinate structures and retaining walls)
1/100	Danger limit for statically determinate structures and retaining walls

Bjerrum [1963]: Data outside brackets

Meyerhoff [1979]: Data in brackets

TABLE IV

Description of standard value	Relative deflection of plain brick walls Subsoil Sand and clay in hard condition	 Clay in plastic condition
a) For multi-storey dwellings and civil buildings		
at L/H ≤ 3	0.0003	0.0004
at L/H ≥ 5	0.0005	0.0007
(L=length of deflected part of wall; H=height of wall from foundation footing)		
b) For one-storey mills	0.0010	0.0010
	(from POLSHIN and TOKAR, 1957)	

Deflection ratio	Type of limit and structure
1/1500	Danger limit for sagging unreinforced load-bearing walls
1/2500	Safe limit for sagging unreinforced load-bearing walls; danger limit for hogging unreinforced load-bearing walls
1/5000	Safe limit for hogging unreinforced load-bearing walls from MEYERHOF, 1979)

This type of approach has also been reconfirmed by the developments of BURLAND and WROTH [1974] and must in any case be associated to the maximum tensile strain of structural materials, a concept already introduced by MEYERHOF in 1956. The definition of this physical characteristic is not as simple as it may appear at first sight, and depends on the overall behaviour of the walls (i.e., material composing the bricks used, their size, mechanical features, type of mortar, its thickness, physical characteristics, etc.).

Table IV shows the significant curvature value supplied by the above authors. Starting from the above concepts, they tried or identify a range of maximum or admissible values for maximum or average settlements in relation to type of structure (i.e., stiffness and use) and foundation soil. These settlements are thus those to which certain characteristic slope and curvature values are associated.

Table V summarizes some important results deriving from the studies and concepts of well-known authors. It should be noted that most authors consider that, although the type of foundation soil may sometimes be ignored, « ordinary » structures may tolerate settlements of 4-10 cm. To obtain the admissible settlements from Polshin and Tokar's data, we reduced the average limit values, dividing them by a coefficient of 1.5 (shown in brackets in Table V/B).

TABLE V/A

Allowable maximum settlement (cm)	Type of soil foundation		Reference
2.5	sand	isolated	TERZAGHI and PECK [1967]
5.0	»	continuous	TOMLINSON [1980]
4.0	»	isolated	SKEMPTON and MCDONALD [1956]
4.5-6.5	»	continuous	» »
6.5	clay	isolated	» »
6.5-10.0	»	continuous	» »

Isolated foundation = plinths and beams
Continuous foundation = slabs and rafts

TABLE V/B

Item no.	Kind of building & type of foundation	Average settlement (cm)
1	Buildings with plain brick walls on continuous and separate foundations with wall length L to wall height H (H counted from foundation footing):	
	L/H ≥ 2.5	8 (5.5)
	L/H ≤ 1.5	10 (6.5)
2	Buildings with brick walls, reinforced with reinforced concrete or reinforced brick belts (not depending on ratio of L/H)	15 (10)
3	Frame buildings	10 (6.5)
4	Solid reinforced concrete foundations of blast furnaces, smoke stacks, silos, water towers, etc.	30 (20)
	(from POLSHIN and TOKAR, 1967)	

4. Measurements of settlements in italian structures

This section reports measurements of settlements and damage (when present) on structures built in Italy, details of which have been published in the last 25 years. The structures are of various types, stiffnesses and uses; examined here are structures in steel, load-bearing brick walls and reinforced concrete, with shallow and deep foundations in granular, cohesive or layered soils.

The range of stiffnesses is very large and goes from flexible structures (steel oil tanks), intermediate-stiffness office and industrial buildings, to high-stiffness structures (reinforced concrete cellular silos).

The behaviour of a total of 69 structures was examined, in 15 of which damage was observed (rotation was considered as damage for stiff structures). Damage measurement was that indicated by the author of the report in question; in this sense this observation, among the data reported, is the only one which may be subjective.

Table VI summarizes the main data of the cases studied, with reference numbers reported in the first column. The following columns show: type of building, structural material, type of foundation, width of building, type of soil, maximum settlement, $\delta\rho/L$ ratio, maximum differential settlement, and possible damage.

It should be noted that no structures with isolated foundations were examined here.

As preliminary analysis, maximum settlement (ρ_{max}) expressed as a function of angular distorsion ($\delta\rho/L$) without differentiating the type of structure, foundation or soil, are reported in a single logarithmic plane (Fig. 3). The general trend reported in Fig. 3 shows good correlation between maximum settlement and angular distorsion.

This circumstance confirms Skempton and MacDonald's observations on the possibility of indicating admissible settlements for structures not only in terms of $\delta\rho/L$ but also using a more practical criterion based on maximum settlement.

In this context, a preliminary observation is that all the structures with settlements greater than 20 cm underwent damage, as already reported by Skempton and MacDonald referring to structures on clays with maximum settlements of 7″ (18 cm). However, this indication is only approximate and cannot therefore be used rigidly. This is because the steel oil tanks examined tolerated settlements greater than those indicated, and those which underwent damage had foundations in concrete of far greater stiffness than that of the superstructure. There are also cases of structures which underwent damage although their maximum settlements were only about 10 cm.

The maximum value of angular distorsion corresponding to $\rho = 20$ cm is 1/650, slightly less than the limit suggested by Skempton and MacDonald.

We therefore examined Skempton and Mac Donalds's original data, shown in Fig. 4. For comparison, this figure groups all the data reported in the above author's paper, only excluding those with maximum settlement of less than 1 cm, without reference to the type of superstructure, foundation, or soil.

The correlation between ρ and $\delta\rho/L$ is always well-defined and clear. The slope of their straight line is smaller, due to the weight of the value of angular distorsions in cases with maximum settlements of less than 5 cm, mainly referring to structures founded on sand. Other factors which may have affected the results are: the presence of a number of structures (tower and steel tanks) with settlements greater than 90 cm which have not been considered in the above mentioned paper. However, in this case too, of the 19 structures with settlements greater than 20 cm, only 2 were not damaged and for them, as in the cases of Fig. 3, all the data are plotted in the quadrant bounded by straight lines $\rho = 20$ cm and $\delta\rho/L = 0.003$.

Figs. 5 and 6 show respectively cases analysed showing type o foundation and nature of foundation soil. The behaviour of the various types of structures seem to be independent of these two factors.

The independence of the type of foundation confirms the views of Skempton and MacDonald and Grant et al.: as regards the nature of foundation soils, it should be noted that the majority of structures examined were built on layered soils.

Fig. 7, showing the $\delta\rho$ (maximum differential settlement) as a function of $\delta\rho/L$ in a logarithmic plane, again shows good correlation between parameters and independence of the trend on structural type of foundations and type of soil. Above the continuous line, with the exception of the oil tanks, almost all the structures underwent damage.

5. Conclusive remarks

In 1955 Skempton and MacDonald identified the parameter $\delta\rho/L$ as the fundamental element on which to judge maximum admissible settlements for structures. This criterion was later confirmed in the works of Grant *et al.* [1975] and Walsh [1981]. Another important approach to the problem was that of Burland and Wroth [1974], based on the criterion of maximum tensile strains.

TABLE VI

Ref. No	Building Type	Blg. material	Foundation	Width (m)	Soil Type	ρ_{max} (cm)	$\delta\rho/L$	$\delta\rho_{max}$ (cm)	Damage	Notes
1 a)	Oil tank	S	DW	36.60	L	27.1	1/390	9.30	tilting	
b)	Steam mill	S	P	23.00	L	4.9	1/6000	0.30		
c)	Steam mill	S	P	23.00	L	3.8	1/6000	0.20		
d)	Power plant serv.	B	P	73.00	L	6.2	1/3600	1.00		
e)	Office building	B	P	12.00	L	2.6	1/6000	0.200		
f)	Chimney	B	P	10.00	L	1.7	1/2500	0.40		
g)	»	B	P	10.00	L	1.2	1/2500	0.40		
h)	Steam turbine bld.	RC	P+DW	11.00	L	2.5	1/10000	0.10		
2	Historical bld.	B	BR	27.00	L	? (3)	1/167	7.10	wall cracking	(3) esteem = 10 cm = ρ_{max}
3 a)	Oil tank	S	AB+WP$_{(1)}$	51.20	L	113.0	1/30	86.00$_{(2)}$	Struct. damage	(1) Anular beam + wooden piles
b)	» »	S	AB+WP$_{(1)}$	51.20	L	118.6	1/26	99.20$_{(2)}$		(2) Between center and beam
c)	» »	S	AB+WP$_{(1)}$	51.20	L	96.1	1/36	71.20$_{(2)}$		
4 a)	Oil tank	S	AB	42.00	S	19.5	1/210	10.00		
b)	» »	S	AB	42.00	S	17.0	1/220	9.50		
5	Office bld.		BR	7.10	L	? (3)	1/185	3.80	struct. wall cracking	(3) esteem = 11 cm = ρ_{max}
7	Silo	RC	P	22.60	L	9.0	1/3300	0.70		
8 a)	Office bld.	RC	RP	20.0	L	1.9	1/9600	0.25		
b)	» »	RC	R	18.0	L	1.5	1/4500	0.40		
c)	» »	RC	R	17.0	L	2.3	—	—		
d)	» »	RC	R	20.0	L	3.0	—	—		
e)	» »	RC	R	26.0	L	2.7	1/8000	0.25	hair type	
9	Power plant	S	R$_{(1)}$	60.6	L	3.0	1/1560	—	cracking	
10	Office bld.	RC	P	20.0	SM	3.0	1/435	2.3		
11	Offce bld.	RC	R	21.4	C	1.8	1/5000	1.2		
12 a)	Steam mill	RC	P	25.3	C + T	—	1/3050	1.1		
b)	» »	RC	P	23.0	C + T	—	1/7500	0.27		
c)	Steam turbine bld.	RC	P	11.0	C + T	—	1/4800	0.5		
d)	» » »	RC	P	11.0	C + T	—	1/4075	0.4		
14	Office bld.	RC	P	42.5	C	3.6	1/1400	1.5		
15	Chimney	RC	P	30.0	L	4.5	1/3000	0.5		
16 a)	Steam mill	S	P	15.0	L	20.0	1/1000	1.9		
b)	Power plant serv.	RC	P	35.0	L	12.0	1/1800	4.0		
c)	Chimney	B	P	19.5	L	13.5	1/600	3.7		
d)	Office bld.	S	P	16.0	L	12.0	1/250	5.4	cracking in brick	

e)	Steam turbine bld.	RC	P	[illegible]	L	[illegible]	[illegible]	[illegible]	[illegible]	
17 a)	Silo	RC	P	48.5	L	80.9	1/350	58.0	tilting cracking	(also ref. no 13)
b)	»	RC	R	12.8		40.0	1/850	20.0	tilt?	
c)	Oil tank	S	R+P	51.2	L	54.2	1/65	$28.8_{(2)}$	cracking	(2) between center and beam
d)	» »	S	R+P	51.2	L	53.0	1/73	$25.1_{(2)}$		
e)	» »	S	R+P	51.2	L	55.5	1/62	$24.8_{(2)}$		
f)	» »	S	AB	51.2	L	35.5	1/295	8.7		
g)	» »	S	AB	67.0	L	81.5	1/65	51.8		
18	Antenna	RC	R	29.0	C	5.7	1/22700	0.06		
19 a)	Oil tank	S	AB	67.0	S	13.0	1/47	70.4		
b)	» »	S	$AB_{(4)}$	69.8	S	—	—	—		(4) on campacted fill
c)	» »	S	$AB_{(4)}$	91.4	S−G	12.5	1/582	7.85		
d)	» »	S	$AB_{(4)}$	96.2	L	—	—	—		
e)	» »	S	$AB_{(4)}$	30.6	L	—	—	—		
20 a)	Silo	S	P	16.0		8.0	1/1200	4.0		
b)	»	RC	P	37.2	S	3.6	1/1200	0.4		
21 a)	Oil tank	S	AB	35.60	L	19.0	1/170	13.0		
b)	» »	S	AB	35.60	L	16.5	1/140	10.5		
c)	» »	S	AB	8.0	L	—	—	4.5		
22	Water tank	RC	AB	50.0	S	8.0	1/500	50		
23	Historical tower	B	R	19.6	L	280	1/13	155	tilting	
24	» »	B	R	19.3	L	120	1/50	35	tilting 2% cracking?	
25 a)	Office bld.	RC	R	11.70	L	19.0	1/600	18		
b)	» »	B	BR	40.0	L	?	1/150	35		
26 a)	Oil tank	S	AB	67.0	L	226	$1/50_{(2)}$	67		(2) between center and beam
b)	» »	S	AB	67.0	C	221	$1/43_{(2)}$	77		(also ref. no 27)
c)	» »	S	AB	87.5	C	223	$1/55_{(2)}$	79		
d)	» »	S	AB	87.5	C	225	$1/87_{(2)}$	50		
e)	» »	S	AB	87.5	C	227	$1/81_{(2)}$			
f)	» »	S	AB	87.5	C	241	$1/84_{(2)}$	52		
g)	» »	S	AB	87.5	C	236	$1/70_{(2)}$	62		
h)	» »	S	AB	87.5	C	285	$1/53_{(2)}$	83		
i)	» »	S	AB	87.5	C	270	$1/77_{(2)}$	57		
28 a)	Oil tank	S	AB	83.5	L	54.0	$1/170_{(2)}$	28	tilting and	
b)	Industrial bld.	S	B	40.0	C	27.0	1/140	8	structural	
c)	Office bld.	RC	R	13.60	L	4.5	1/2700	0.5	damage	
d)	Water tower	RC	R+P	17.00	L	24.0	1/187	8.0	tilting	

KEY: *Building Material*: S = steel, RC = reinforced concrete, B = brick wall; *Foundattion*: DW = diaphragm wall, P = pile, BR = brick raft, AB = anular beam, R = raft; *Soil Type*: C = clayey, S = sandy or granular, T = tuff, L = layered.

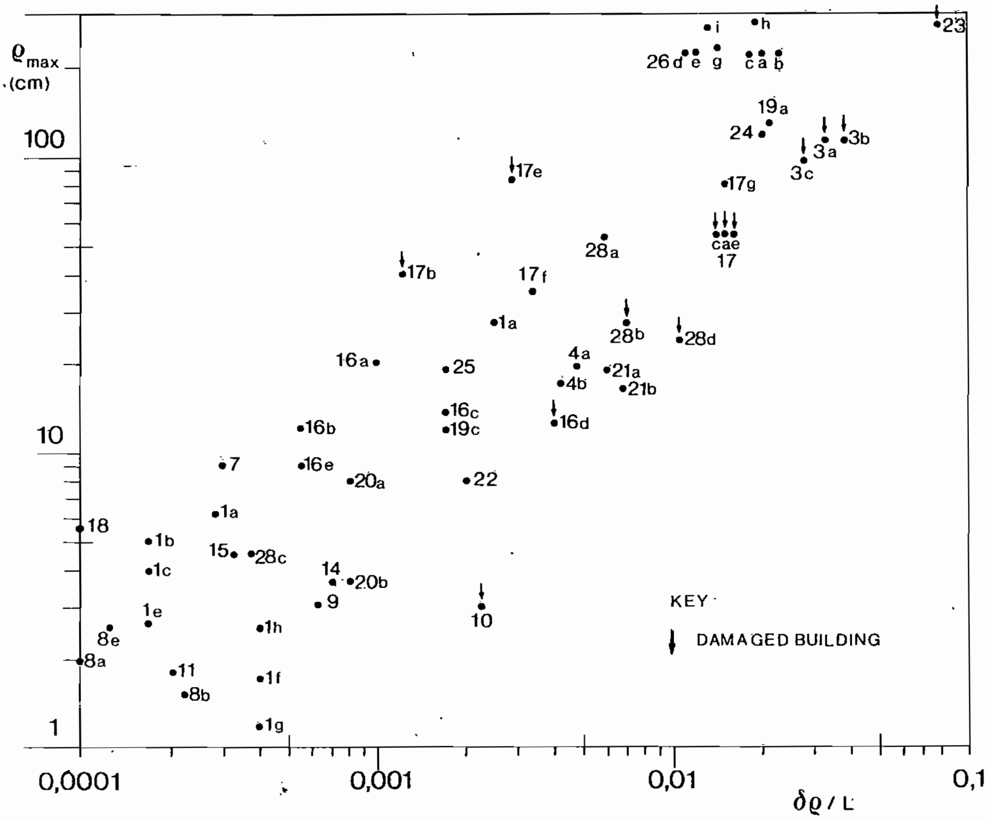

Fig. 3. - Maximum settlements of structures as a function of angular distorsions.

Fig. 3. - *Massimi cedimenti di strutture in funzione delle distorsioni angolari.*

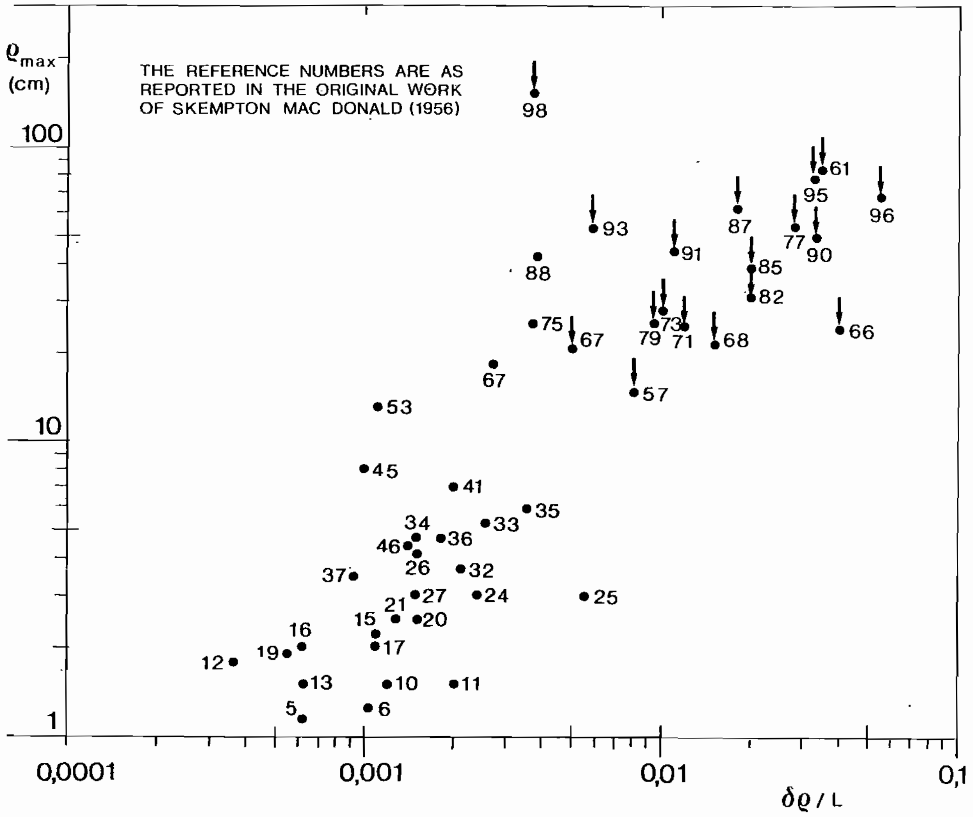
THE REFERENCE NUMBERS ARE AS REPORTED IN THE ORIGINAL WORK OF SKEMPTON MAC DONALD (1956)

Fig. 4. - Skempton, MacDonald's Data.

Fig. 4. - *Dati di Skempton-MacDonald.*

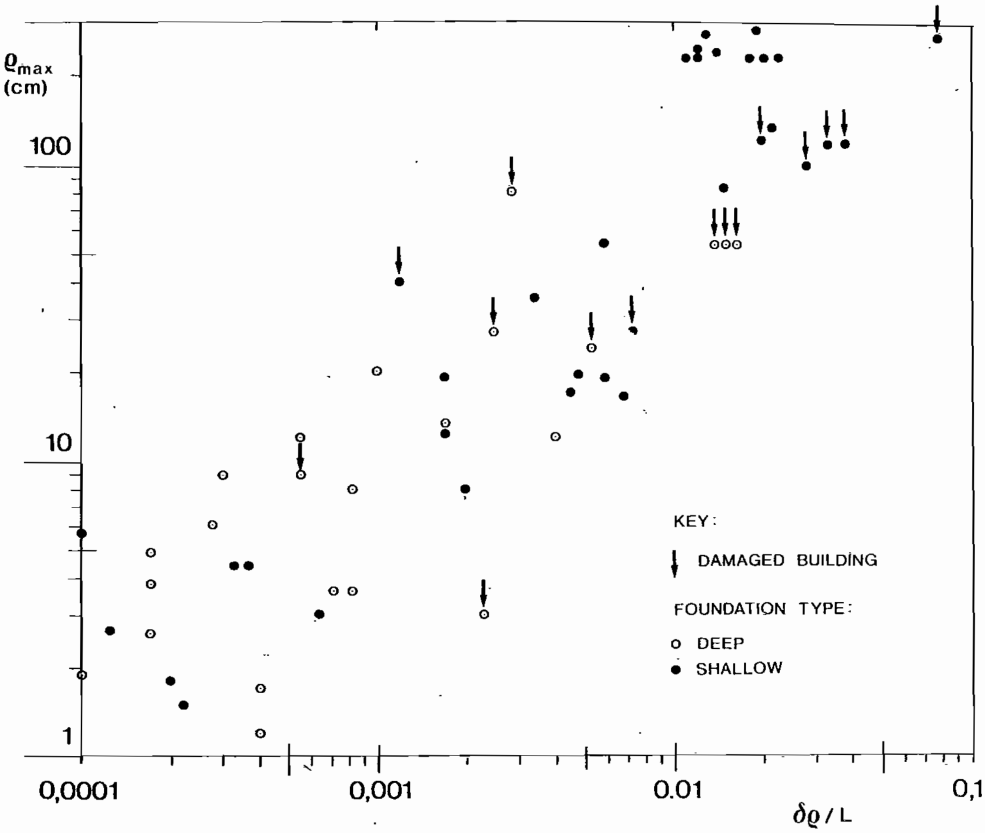

Fig. 5. - Correlation between ρmax and δρ/L for deep and shallow foundations.

Fig. 5. - *Correlazione tra ρmax e δρ/L per fondazioni profonde e superficiali.*

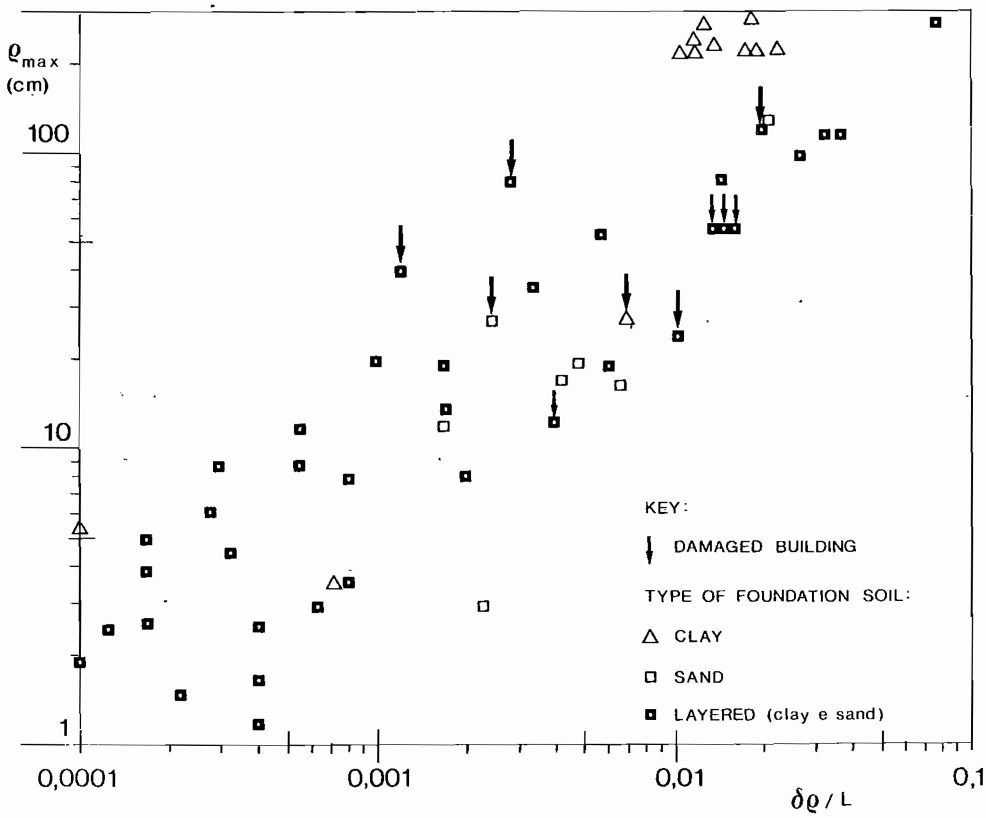

Fig. 6. - Correlations between ρmax and δρ/L for different foundation soils.

Fig. 6. - *Correlazione tra ρmax e δρ/L per differenti terreni di fondazione.*

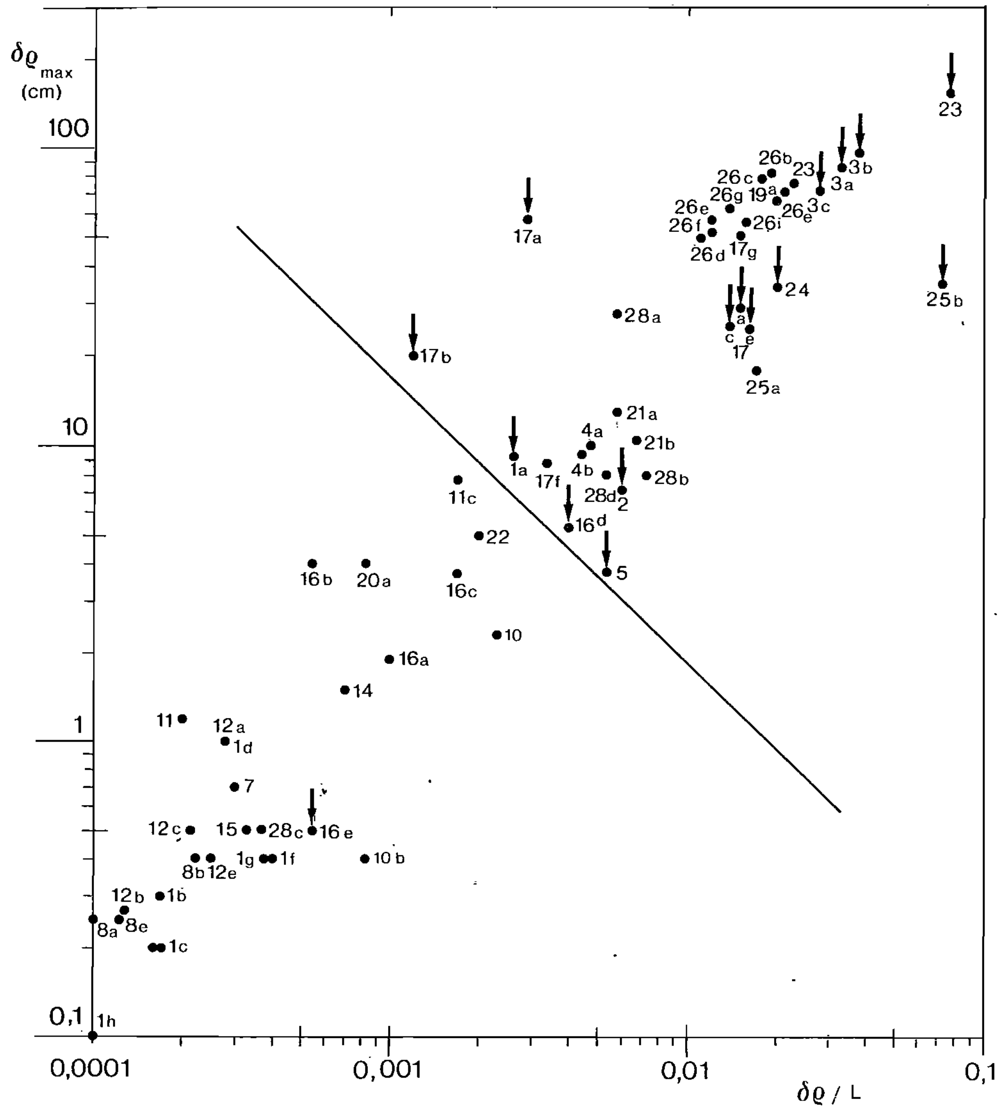

Fig. 7. - Maximum differential settlements of structures as a function of angular distorsions.

Fig. 7. - *Massimi cedimenti differenziali di strutture in funzione delle distorsioni angolari.*

The data reported in the literature on the cases examined allowed study of the problem by using the first of the two criteria. In effect, in almost all the publications examined, there are very few elements allowing evalution of parameters required for application of the second criterion of analysis.

Our analysis showed significant correlation between maximum settlement and angular distortions. This shows that the admissibility of deformation may be expressed on the basis of the value of maximum settlement calculated, rather than attempting an estimate of the angular distorsion, which is definitely more complex.

The calculated values may highlight possible problems and reveal the necessity for extending study on the case in question.

One method of approaching the problem, already suggested by Cooling [1956] is that of calculating settlement in the preliminary hypothesis of a flexible structure and, according to the values found, judging the admissibility of settlement or, alternatively, the necessity of going deeper into the problem.

On the basis of observations carried out, settlements of less than 8 cm should not lead to serious problems. Settlements of more than 20 cm are not tolerated by traditional structures and damage should be anticipated, the extent of which depends on the relative oil/structure stiffness. Foreseeable damage can also be accepted in relation to the structure's destined use.

For settlements of between 8 and 20 cm, further tests on the interaction between soil and structure must be carried out.

It should be borne in mind that settlement calculation may involve an error of up to 50%

so that, as suggested by Meyerhof, a maximum safety factor of 1.5 should be adopted.

The values indicated here should of course be understood as useful indications and not as rigid design rules. Moreover, special structures may differ — sometimes markedly — from the behaviours indicated and may be planned to tolerate higher settlements.

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SOMMARIO

Analisi dei cedimenti ammissibili nelle strutture

Nell'articolo si considera una estesa casistica di strutture realizzate in Italia prendendo in esame l'ammissibilità dei cedimenti in relazione alla tipologia delle strutture in elevazione, delle opere di fondazione e del tipo di terreno.

È ben noto infatti che l'osservazione dei cedimenti e degli eventuali danni in strutture costituisce un valido metodo per valutare i limiti entro i quali un certo manufatto può accettare deformazioni.

Per sviluppare questo tema si presenta nel paragrafo 2 e 3 lo stato dell'arte desunto dalla letteratura internazionale. Nel paragrafo 3 in particolare si definisce la terminologia generale chiarendone l'evoluzione storica.

Si definiscono così: il cedimento, il cedimento differenziale, la rotazione, la pendenza (distorsione angolare), l'inflessione relativa e la curvatura (rapporto di inflessione).

I principali risultati « storici » sono presentati nelle tabelle I, II, III, IV e V; che permettono una chiara visione sintetica dei limiti di ammissibilità dei cedimenti facendo diferimento ai termini precedentemente definiti.

Dopo questa fase di introduzione al problema vengono analizzati, nel paragrafo 4, i rilievi dei cedimenti e danni, quando presenti, relativi a strutture realizzate in Italia, pubblicati negli ultimi 25 anni. Si tratta di strutture di vario tipo, di diverse rigidezze e destinazione d'uso.

Vengono prese in esame struture metalliche, in muratura portante ed in cemento armato, con fondazioni superficiali e profonde in terreni granulari, coesivi o stratificati.

Il campo delle rigidezze è molto ampio e va da strutture flessibili (serbatoi metallici) a strutture di rigidezza intermedia (edifici civili e industriali) fino a strutture di elevata rigidezza (sili cellulari in c.a.).

Complessivamente è stato esaminato il comportamento di 69 strutture in 15 delle quali sono stati osservati danni (anche la rotazione è stata considerata danno per le strutture rigide). Il rilievo dei danni è quello indicato dall'autore dell'articolo; in questo senso tale osservazione è l'unica, tra i dati riportati, che può risentire di un giudizio soggettivo.

In tab. IV sono riassunti in modo schematico i principali dati che caratterizzano i casi studiati con le indicazioni bibliografiche riportate nella prima colonna.

Come prima analisi sono stati riportati in un piano logaritmico (fig. 3) il massimo cedimento (ρ_{max}) espresso in funzione della distorsione angolare ($\delta\rho/L$) per tutte le strutture.

Dall'andamento generale riportato si nota una buona correlazione tra cedimento massimo e distorsione angolare.

Tale circostanza conferma quanto già asserito da Skempton e McDonald sulla possibilità di indicare i cedimenti ammissibili per le strutture non solo in termini di $\delta\rho/L$ ma anche con un più pratico criterio basato sul cedimento massimo.

Si è notato infatti che tutte le strutture che hanno avuto un cedimento superiore ai 20 cm hanno subito dei danni. Tale indicazione è di larga massima e non può quindi costituire un criterio rigido.

Infatti i serbatoi metallici hanno tollerato cedimenti superiori di un ordine di grandezza a quelli indicati; tra i serbatoi metallici quelli che hanno subito danni avevano fondazioni in calcestruzzo di rigidezza ben maggiore di quella della sovrastruttura.

Inoltre esistono casi di struture con cedimenti massimi dell'ordine di dieci cm che hanno invece subito dei danni.

Il valore limite della distorsione angolare corrispondente a $\rho_{max} = 20$ cm è di 1/650 che risulta di poco inferiore al limite suggerito da Skempton e McDonald.

Nelle figure 5 e 6 sono rispettivamente riportati i casi analizzati con le indicazioni della tipologia delle fondazioni e della natura dei terreni di fondazione.

Si può osservare che il comportamento dei vari tipi di struttura sembra essere indipendente da questi ultimi due fattori. L'indipendenza della tipologia di fondazione conferma quanto già indicato da Skempton e McDonald, Grant et al. per quanto riguarda la natura dei terreni di fondazione va segnalato che in prevalenza sono stati esaminati casi relativi a terreni stratificati.

I dati riportati in letteratura sui casi esaminati hanno permesso lo studio del problema utilizzando il criterio di Skempton e Mac Donald; in quasi tutte le pubblicazioni esaminate mancano infatti gli elementi utili per valutare i parametri richiesti per l'applicazione del criterio di analisi proposto da Burland e Wroth.

L'analisi effettuata ha mostrato una buona correlazione tra cedimento massimo e distorsioni angolari.

Ciò indica la possibilità di poter esprimere l'ammissibilità di una deformazione in base al valore del cedimento massimo calcolato piuttosto che tentare una stima della distorsione angolare che risulta decisamente più complessa.

Il valore calcolato può costituire una valida indicazione preliminare sui problemi che possono presentarsi e sulla necessità di dover approfondire ed estendere lo studio del caso in esame.

Sulla base delle osservazioni eseguite si può ritenere che un cedimento inferiore agli 8 cm non sia tale da far insorgere sensibili problemi. Cedimenti maggiori di 20 cm non vengono tollerati dalle tradizionali strutture; sono quindi da prevedersi dei danni la cui entità dipende dalla rigidezza relativa terreno-struttura. I prevedibili danni possono essere anche accettati in relazione alla destinazione d'uso della struttura.

Per i cedimenti intermedi è necessario procedere ad un più approfondito esame sulla interazione tra terreno e struttura. Bisogna tener presente che il calcolo dei cedimenti può essere errato del 50%, sarà quindi opportuno adottare, come suggerito da Meyerhof un valore minimo del coefficiente di sicurezza pari a 1.5.

Si avverte che i valori qui indicati devono essere intesi come utili indicazioni e non come rigide regole di progetto e che strutture particolari possono discostarsi, anche notevolmente, dai comportamenti indicati e possono essere progettate per sopportare cedimenti più elevati.