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Influence of Soil Behaviour on Structural Design

L'influence du comportement des sols sur le dimensionnement des structures

Der Einfluss des Bodenverhaltens auf die Bemessung von Bauwerken

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SUMMARY
This report accentuates the need for bridge engineers to liaise closely with geotechnical engineers in situations where the training and experience of the former place a limit on their ability to cope with the relevant geotechnical problems.
Proper management and autonomy of the design team is imperative in situations where the bridge engineer has insufficient experience to make geotechnical judgements.

RESUME
Ce rapport relève l'importance d'une collaboration étroite entre l'ingénieur staticien et le géotechnicien là où l'expérience du premier ne suffit plus pour faire face aux problèmes géotechniques. Cette collaboration doit être réglée de façon impérative au sein d'une équipe de projet.

ZUSAMMENFASSUNG
Dieser Bericht weist auf die Bedeutung einer guten Zusammenarbeit zwischen Brückeningenieur und Geotechniker hin in Situationen, wo die Erfahrung des erstgenannten nicht ausreicht, um mit den geotechnischen Problemen fertig zu werden. Diese Zusammenarbeit muss innerhalb einer Entwurfsgruppe sichergestellt sein.

1. INTRODUCTION

In the Spring of 1971 the Institution of Structural Engineers in Great Britain provided active support to a proposal by members of the Institution that recognition should be given in general design practice to interactive effects together with the need to stimulate research on the physical response of structures to foundation movements. In November 1977 a state-of-the-art report on Structure-Soil Interaction relating to buildings and bridges was produced by this Institution.

The state-of-the-art report emphasised how essential it is for design purposes that the possibility of ground movements should be recognised, and, where anticipated, that they should be quantified.

This apparently simple statement implies that:

a. The physical structure of the ground, the groundwater regime and the characteristics of the superficial and solid deposits can be defined.

b. The design solution is sufficiently advanced for the structural loads and their disposition to be assessed.

c. Theoretical methods of prediction or empirical relationships based on experience exist whereby ground movements can be quantified.

The requirements of (a) are met by adequate site investigation work. Progress towards the final design solution is generally an iterative process involving (b) and (c) using the information accumulated on (a).

The current state-of-the-art, or knowledge, of interactive analysis is not extensive and many senior engineers have dealt with such complex problems successfully by using empirical techniques derived from long experience.

In many instances a practical acquaintance with bridge performance can be of more direct value in design to engineers than rigorous theoretical predictions since experience often provides better design information than analytical procedures based on poor physical models. However complete reliance on knowledge of behaviour as providing universal solutions to problems can be dangerous because of the natural limitations on knowledge generally possessed by individual engineers. The complex nature of soils does not permit universal application of empiricism since relationships based on observation may change radically with varying boundary conditions.

The limitations on the use of empiricism in design practice are demonstrated by a study of the situations under which problems have arisen. Generally failures have resulted from a significant departure from routine patterns of loading, traditional types of structure and familiar ground conditions. Sometimes a lack of awareness of the importance of significant changes in such factors causes difficulty and only serves to emphasise the problems confronting the engineer who attempts to extrapolate beyond his relatively limited knowledge and experience.

The bridge engineer would be prudent to obtain the advice of the geotechnical engineer in unfamiliar geological situations with the clear realisation that only the bridge engineer has a full understanding of the ability of the structure to deform and transfer stress. The geotechnical engineer can determine the soil characteristics, assess the physical structure of the ground and predict the probable ground deformations for a given set of loads and structural rigidity but the performance of the bridge is the sole responsibility of the bridge engineer since he along controls both loading and rigidity.

The prime role in the design team is played by the bridge enginer and the invaluable supportive role is played by the geotechnical engineer.

Design management is, therefore, as important as good structural design and the bridge engineer must ensure that the efforts of the design team, including the work of the geotechnical engineer are properly co-ordinated. There is a distinct difference between the bridge engineer (1) making a sound judgement based on specialist advice from the geotechnical engineer and (2) surrendering the making of decisions on portions of his design to the geotechnical engineer.

The deliberate transfer of decision-making to engineering specialists does not diminish the responsibility of the bridge engineer for the competence of the complete structure. Extreme conservatism or the potential for failure can result from fragmentation of the design process.

2. DESIGN PHILOSOPHY

The criteria for sound economic design embrace the following considerations:

a. An appreciation of ground movements and related interactive effects.

b. A careful appraisal of the theoretical concepts used for analytical purposes.

c. An awareness of the difficulties of obtaining characteristic soil parameters.

d. An understanding of the benefits provided by simplicity of design and construction.

e. A recognition of the advantages of good design management.

An infinitely rigid foundation exists only as a hypothesis for the simple analysis of structures. Numerous bridge structures are associated with embankments on soft compressible soils and the resulting ground movements in the vicinity of the abutments and bankseats affect the design and performance of these structural elements. Interactive effects on bridge structures are inevitable in situations where foundations are subjected to relative displacements. The bridge engineer may choose to ignore these secondary effects and design the structure on the assumption of unyielding supports, but the interaction will nevertheless be experienced and its effect may be more than envisaged.

Interactive effects can be directly caused by ground movements unrelated to the construction of the highway embankments or bridges. The effects of mining subsidence on a bridge can be of greater severity than those directly associated with the construction of the bridge and associated embankments. Other indirect causes of interaction are the construction of new buildings, basements and tunnels in an urban situation, ground displacements and vibrations due to blasting and pile-driving operations, seismic excitation and river scour effects.

The geotechnical engineer can assist the bridge engineer in the identification of probable sources of ground movements and can quantify the displacements.

The bridge engineer should examine the validity of the physical models used in his theoretical analyses and compare his idealisations with reality. The same duty should be imposed on the geotechnical engineer and consequently the compatibility of the soil and structural models should be examined and approved by the bridge engineer. As a general rule the degree of sophistication adopted by the bridge engineer should be related to that employed by the geotechnical engineer for idealisation of the behaviour of the soil mass. Sophisticated and rigorous analytical solutions to design problems are not always appropriate or necessary and a high order of sophistication is only valid if all variables can be defined. Lack of definition of variations in ground conditions can render structural analyses meaningless and result in completely misleading predictions of interactive effects. If the physical structure of the ground is complex and cannot be defined at reasonable cost then sophisticated analyses are inappropriate and simple design methods provide better aids to judgement.

The training and experience of the geotechnical engineer provide him with an awareness of the difficulties of determining characteristic soil parameters and it is essential that these problems of definition of real parametric values are conveyed to the bridge engineer. The intrinsic variability of soils both in physical structure and properties should not however, either deter the geotechnical engineer from assessing upper and lower limits of behaviour to aid the judgement of the bridge engineer or be presented as an excuse for inadequate or inappropriate site investigation work.

The bridge engineer should not be too specific at an early stage in the design process if advantage is to be taken of the specialist advice of the geotechnical engineer who is often able to make early predictions of the orders of magnitude of relative displacements without recourse to refined calculations and comprehensive investigations.

As a corollary, it is essential that the geotechnical engineer should be involved in the design process at as early a stage as possible since any adverse effects of interaction can be kept within acceptable limits by proper design and construction techniques.

Simplicity of design and construction in situations where relatively large ground movements are anticipated is of paramount importance and the bridge engineer should examine the ability of his design to accommodate or resist the probable relative displacements predicted by the geotechnical engineer. Simplicity may also lead to overall project economy since apparently cheaper sophisticated designs can involve longer construction times with the resulting cost penalties. A balance must be sought between the material savings indicated by a sophisticated solution and the time savings in constructing a relatively conservative simple bridge. The elegance or aesthetic appeal of a bridge is not necessarily compromised by the adoption of simplicity in design and construction and simplicity of concept can provide the bridge engineer with the facility to accommodate the anticipated ground movements. The geotechnical engineer is confronted by sufficient natural complexities without artificial restraints on predictions of performance being imposed by complex bridge designs.

The essential requirement for good design management cannot be over-emphasised and the bridge engineer occupies the prime function. The secondary role performed by the geotechnical engineer is of major importance in analysing the situation and advising the bridge engineer, and the timing of the involvement of the former is critical to the design process. Late involvement of the geotechnical engineer may result in the adoption of inappropriate solutions. Intermittent and infrequent involvement of the geotechnical engineer may also result in fragmentation of approach and lack of coherence of solutions to the various geotechnical problems. Autonomy and unity of effort will ensure that there is adequate communication of concept and detail between the bridge engineer and the geotechnical engineer.

3. DESIGN PROCESS

The geotechnical engineer may be involved with the following aspects of bridge design:

a. Stability and performance of abutments and bankseats

b. Stability and performance of shallow spread footings

c. Stability and performance of pile foundations

d. Effects of downdrag and lateral soil displacements on piled bridge abutments caused by highway embankments on soft compressible soils

e. Assessment of lateral soil pressures on abutments and wingwalls

f. Effects of mining subsidence

g. Stability and performance of land and river cofferdams, including scour effects

h. Effects of construction on permanent works

Structures with asymmetrical load distribution on soft soils have a potential for instability where the ratios of applied stress to limiting stress are high. This situation can exist where high embankments and associated bridges are constructed either on deep soft alluvium or adjacent to river channels.

The geotechnical engineer can analyse the particular situation in terms of total and effective stresses to advise the bridge engineer on the probable short and long term stability of the abutment or bankseat configuration and choices of foundation solution. A piled foundation does not necessarily ensure stability in situations of asymmetrical load distribution on deep very soft soils.

Although there are well-established procedures available to the geotechnical engineer for stability analyses an adequate definition of the variations in the physical structure and characteristics of the underlying soil is essential. Proper methods of sampling and field testing are necessary if the characteristics of soft cohesive soils are to be determined with acceptable accuracy for refined methods of stability analysis. Continuous piston sampling of soft cohesive soils and meticulous examination and comprehensive description of air-dried split samples are essential pre-requisites for the assessment of the intrinsic properties of the soil mass. The inevitable variations in soils necessitate some reliance on engineering judgement and a study is often made by the geotechnical engineer of the sensitivity of solutions to variations in important soil properties, and the physical structures, as an aid to judgement. The bridge engineer places considerable reliance on the judgement of the geotechnical engineer to correctly interpret the situation since mass failure of soft soils under major asymmetric loading cannot be prevented by normal abutment designs.

In water-bearing fine-grained non-cohesive soils it is common experience that the standard penetration test is difficult to perform at depths appropriate to piled foundations. There is a trend within the U.K. and U.S.A. for geotechnical engineers to make greater use of the static penetration test in fine-grained non-cohesive soils for the design of piled foundations although the standard penetration test will continue to be used for the design of shallow foundations. The electrical cone penetrometer of simple cylindrical shape is generally used in preference to the mechanical cone penetrometer of variable profile. The properties of non-cohesive fine-grained soils can be determined from the cone resistance and friction ratio diagrams obtained from static penetration tests and the geotechnical engineer can interpret this data to the advantage of the bridge engineer.

Shallow spread footings can be appropriate for many situations and piled foundations need not be a first consideration by the bridge engineer. Circumstances have arisen where unrealistic criteria for relative rotation have been adopted by bridge engineers for the design of bridge decks. The ground movements predicted by geotechnical engineers are generally of such magnitude that unless the bridge engineer permits reasonable relative displacements of the bridge deck, piled solutions are inevitable.

The measured resistances obtained from the standard penetration test are corrected for the effects of overburden pressure for the design of shallow spread footings and the correction chart, Figure 1, has been widely adopted in the U.K. by geotechnical engineers.

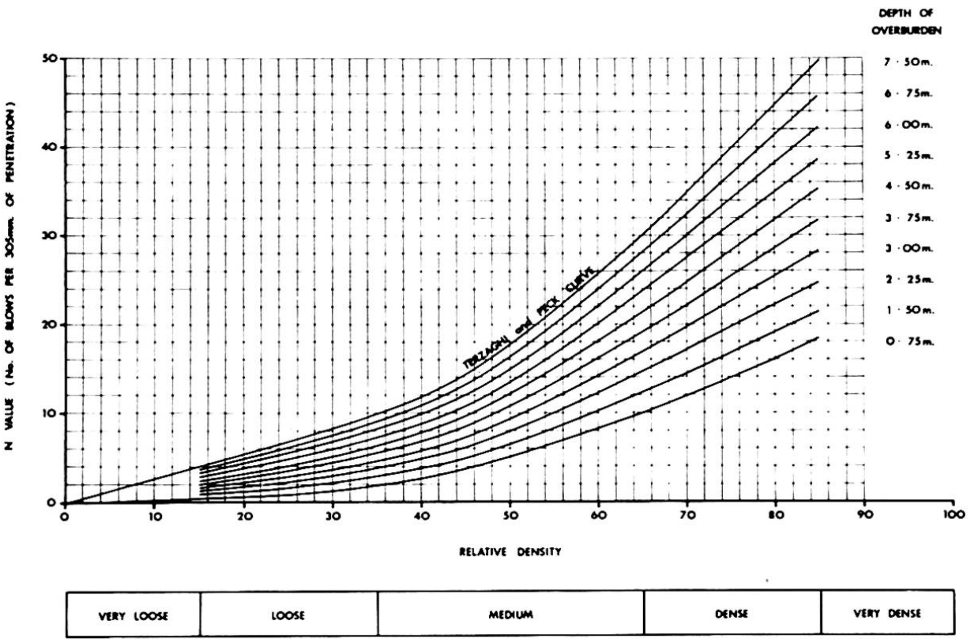


Fig. 1 S.P.T. Correction Chart

The measured cone resistances obtained from the static penetration test can be used to determine the undrained strengths of cohesive soils using empirical relationships similar to that shown on Figure 2. The stress histories of cohesive soils can also be assessed from the cone resistances from an examination of the intercepts of the mean lines of the linear portions of the resistance diagrams projected to groundsurface. If the bridge foundations will not impose a load in excess of the over-consolidation stress on the soil the long term consolidation settlements will be acceptable for most types of bridge.

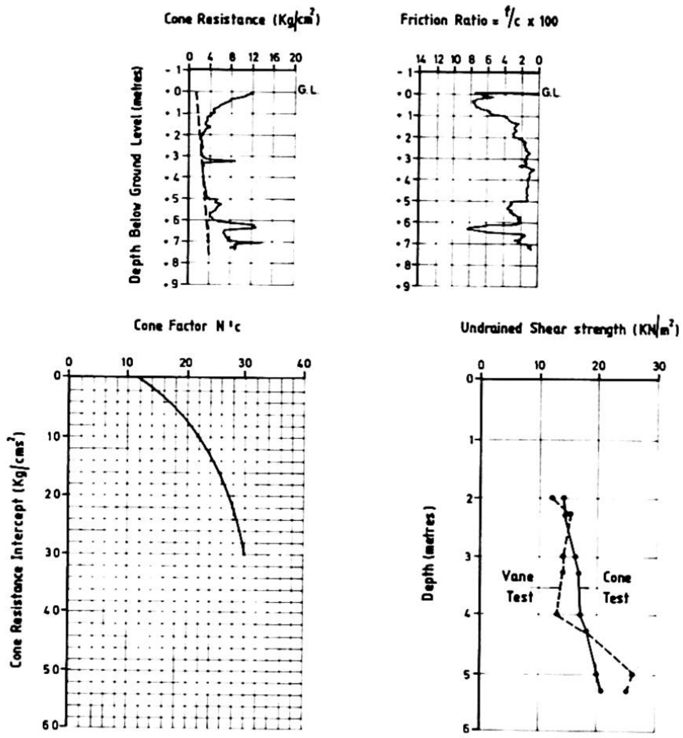


Fig. 2 Cone Factors for Cohesive Soils

In situations where the bridge loads are in excess of the capacity of the soils to support the piers and abutments, piled foundations are often utilised. Bridge abutment piles inclined backwards beneath highway embankments are subject to flexural effects due to embankment settlement and should be avoided by the bridge engineer.

The design of piled foundations founded in fine-grained non-cohesive soils preferably should be based on the results of static cone penetration tests and the limitations on pile capacity depending on depth of embedment in the bearing stratum should be assessed by the geotechnical engineer.

The geotechnical engineer is familiar with the numerous criteria affecting pile capacity and foundation settlement and can guide the bridge engineer in the design of suitable piled foundations for a particular geological situation.

Piled foundations supporting bridge bankseats are subject to downdrag forces caused by the settlement of associated highway embankments where these are constructed on soft compressible soils. The geotechnical engineer can assess the downdrag forces in terms of effective stresses and provide the bridge engineer with the allowances which must be made in design for downdrag effects. The geotechnical engineer can also advise the bridge engineer on the problem of translation and rotation of bridge abutments related to lateral displacements of piled foundations caused by embankment settlement behind the bridge abutments. The settlement of embankments on soft soils behind bridge abutments can also affect highway performance due to local 'dishing'.

The design of bridge abutments involves an assessment of lateral soil pressures which is often solved in an empirical and unsophisticated manner with little consideration given to wall deformations or the high stresses induced by compaction of the backfill materials.

The Coulomb or Rankine theories are frequently adopted but Coulomb did not consider the state of stress within the backfill and the Rankine approach assumes that soil failure is associated with a neglible displacement of the backfill. Rowe has stated that the use of Coulomb's equation as the entire basis for teaching and research imposes a severe restriction on the development of soil mechanics, since the Mohr-Coulomb criteria ignore volume change. It is important to emphasise that volume change in shear is one of the most important properties idigenous to soils.

Terzaghi executed large-scale retaining wall tests in 1929 and demonstrated that the following parameters may be expected for a loose sand backfill having an angle of shearing resistance of 34° for different values of the lateral yield of the wall.

Lateral Yield of Wall as a fraction of Wall height (H)	Active earth pressure coefficient (Ka)	Angle of Wall Friction (degrees)		Mobilised angle of shearing resistance (degrees)	
0	0.405	21	20'	19	30'
0.00004	0.371	26	0'	20	50'
0.00014	0.320	25	30'	25	10'
0.00083	0.279	26	40'	28	40'
0.00500	0.247	26	20'	32	20'

In contrast to the performance of loose sand backfill, the lateral soil pressures measured by Terzaghi for dense sand attained the minimum value at a yield of 0.001 H and additional yield resulted in a steady increase of the lateral pressure. Vibrations reduced both the angle of wall friction and the mobilised angle of shearing resistance for both loose and dense sand backfills. The dependency of lateral soil pressure on wall displacements is well-known to geotechnical engineers who can provide the bridge engineer with design values related to rigidity of the abutment walls.

Peak values for angle of shearing resistance and angle of wall friction should not necessarily be used in theoretical solutions for active and passive pressures.

Figures 3 and 4 which are presented by Rowe are fundamental and worthy of study by bridge engineers as a means of understanding the stress-strain relationships which must be considered by the geotechnical engineer before making design recommendations.

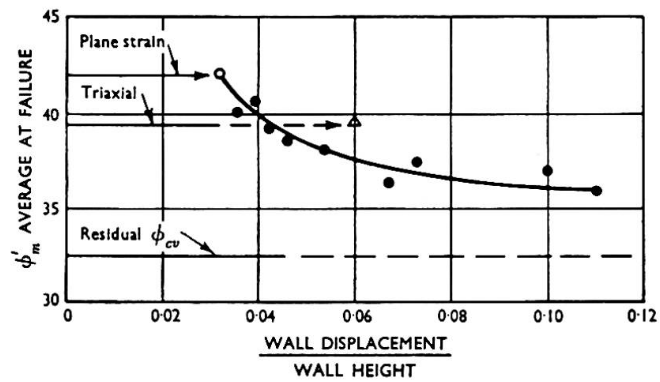


Fig. 3 Relationship between ϕ'_m at Kp max. and wall displacement for dense sand.

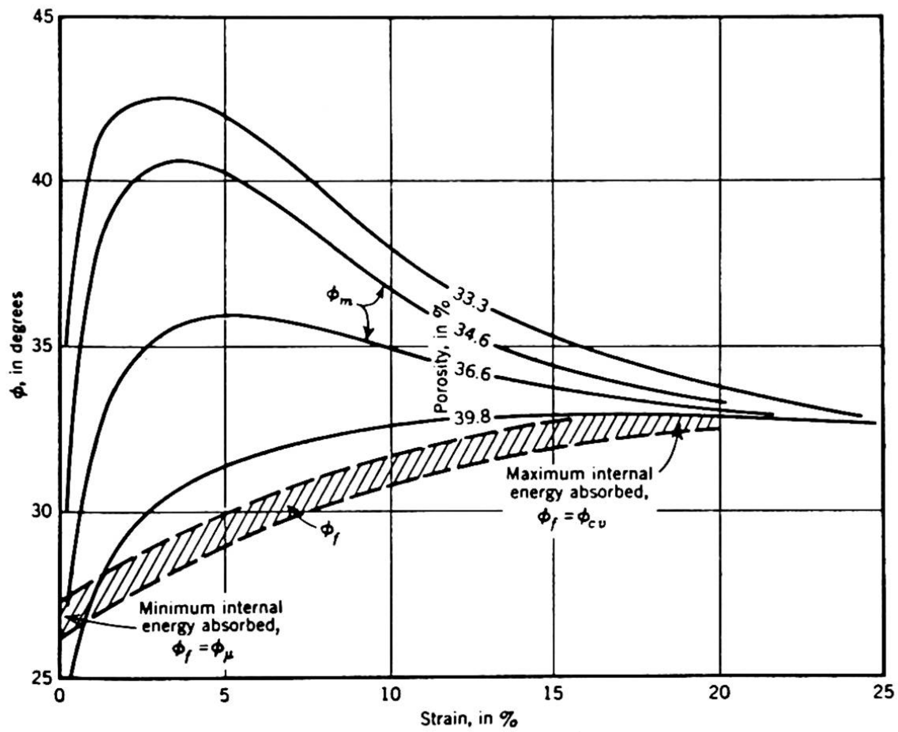
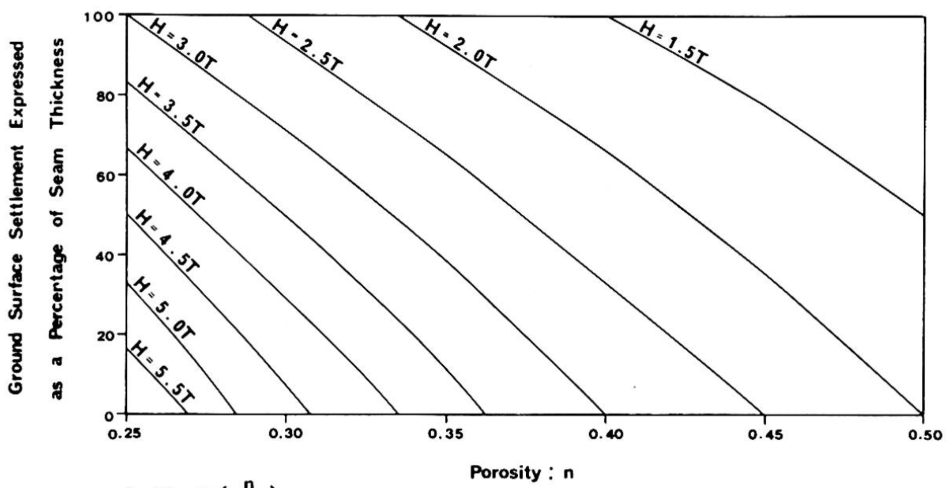


Fig. 4 Unique relation between Ø and strain

Mining subsidence introduces an event into the life of a bridge structure which is outwith the control of the bridge engineer. The ground displacements are unrelated to the weight of the bridge and are often of greater severity than those which would be caused by the imposition of the same structure on a yielding foundation.

The displacements of the groundsurface may be predicted with reasonable accuracy in the case of modern active mining but old pillar and stall workings and old mine shafts can cause local and severe ground displacements. The geotechnical engineer can predict the magnitude of the displacements using prismal theory and Figure 5 presents the theory in graphical form.

GROUND SUBSIDENCE PREDICTIONS USING PRISMAL THEORY



$$S = 2T - H\left(\frac{n}{1-n}\right)$$

where S is ground surface settlement.

T is seam thickness.

H is thickness of rock cover.

n is Porosity of rock material after roof failure.

Fig. 5 Ground Subsidence Chart

The stability of temporary and permanent works for bridge piers within river channels is a matter of some complexity and early and close collaboration between the bridge engineer and the geotechnical engineer is beneficial to the design process. Interactive effects between the pier structure and the soil are often inevitable since the construction of a pier within a restricted river channel changes the stream velocities and flow patterns and Figure 6 indicates in an approximate manner the readiness with which soils are scoured by relatively low stream velocities.

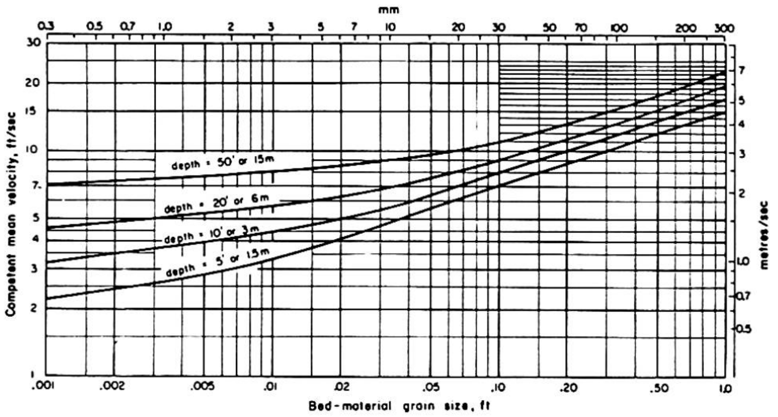


Fig. 6 Approximate relationship for river bed scour

Construction works executed in close proximity to existing bridges can cause indirect interactive effects and affect the performance of a long established bridge structure. Ground vibrations and displacements caused by pile-driving or dynamic consolidation, groundwater lowering, adjoining deep excavations and tunnelling can cause problems. Pile-driving operations using displacement piles in close proximity to river banks can generate excess porewater pressures in soft saturated soils and endanger slope stability.

The assessment of seismic excitation on bridge structures is a mandatory requirement in earthquake zones and the effects of the ground vibrations on soils require due consideration. Saturated loose sands and silts may experience compaction, and liquefaction can be a major hazard. Settlement of the order of 17% of the layer thickness would result for the idealised model of sand consisting of spheres of equal dimensions experiencing compaction from the loosest state to the densest state.

It may be assumed that sands with relative densities less than 50% will experience compaction and cause significant settlement.

In general, interactive effects for bridge structures founded on bedrock can be ignored but it would be prudent to assess the interactive behaviour for anchorages of suspension bridges and the high stresses imposed on rock strata by arch bridges. The geology of the site is very important and planes of separation and the nature and condition of rock strata require careful investigation and identification.

The geotechnical engineer can assess the degree of severity of these events; provide the bridge engineer with appropriate solutions and assist with the important consideration of the influence of soil behaviour on the choice of bridge.

In conclusion the terms of reference to the reporter specified that the content should present matters where collaboration between bridge engineers and geotechnical engineers was of benefit to bridge design with special emphasis on interactive effects(Structure-Soil Interaction) and it is hoped that interest in the subject will be stimulated by this general report.

There is a growing awareness within the U.K. and U.S.A. of the need to consider interactive effects and develop new design methods which recognise the effects of ground displacements. Even if it is argued by some that there is no apparent advantage in making significant changes to current design methods because of small cost savings the desire to improve our analytical models, and ensure our idealisations compare favourably with reality, should be a sufficient incentive for close collaboration.

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