sloping soil surface. In this paper correction factors are developed to account for the intrinsic randomness of soil and load parameters. These correction factors are expressed as functions of the mean values and variances of the soil unit weight, the cohesion intercept and friction angle of the soil, and the applied load. These correction factors are developed based on a second moment theory that includes the correlation between the bearing capacity factors. However, the analysis does not account for difficult to quantify uncertainties such as those associated with soil parameter determination techniques and the method of analysis.

It is concluded that with only slight modification the bearing capacity equation can be made to account for the varations in random soil parameters. It is also concluded that this modification presents a more rational approach to design in that the design satisfies a required reliability, or probability of success, and not an arbitary factor of safety.

REFERENCES

1. TV Galambos, B Ellingwood, JG MacGregor & CA Cornell, Probability Based Load Criteria: Assessments of Current Design Practice, J.Str.Eng.(ASCE), 108(ST5), May 1982.
2. ME Harr, Mechanics of Particulate Media: A Probabilistic Approach, McGraw-Hill, New York, 1977.
3. TS Ingra, & GB Baecher, Uncertainty in Bearing Capacity of Sands, J.Geot.Eng.(ASCE), 109(7), July 1983.
4. IK Lee, W White & OG Ingles, Geotechnical Engineering, Pitman, Marshfield, Mass., 1983.
5. R Rackwitz, Practical Probabilistic Approach to Design - First Order Reliability Concepts for Design Codes, Comate European du Beton, Bulletin D'information, 112, Munich, West Germany, July 1976.
6. H Winterkorn, & HY Fang, Foundation Engineering Handbook, Van Nostrand Reinhold, New York, 1975.

HUMAN FACTORS AND COMMUNICATION PROBLEMS IN FOUNDATION ENGINEERING

J. C. Santamarina, A.M.ASCE[1] and C. J. Turkstra, F.ASCE[2]

ABSTRACT: Recent findings in non-engineering fields related to human factors are reviewed with emphasis on communication difficulties. Foundation engineering tasks are discussed in the context of their potential for problems related to human factors. In particular, case histories are used to demonstrate the significant influence of subformal communication and on-site decisions. The paper concludes with a discussion of alternative measures to reduce the negative effects of human factors. It is expected that increased awareness of these biases and limitations will stimulate efforts to reduce their effect.

INTRODUCTION

During the past several years, the vital role of human factors in civil engineering has become widely recognized. Conferences to discuss the causes and control of errors and oversights in design and construction have been organized by the Engineering Foundation, the IABSE, the US Army and the ASCE among others. The quality of construction and the prevention of failures are of such public concern that the House of Representatives of the Government of the United States issued a major report on the subject [1]. "Communications and organization in the construction industry" were listed as primary causes of failures. The recent ASCE "Manual of Professional Practice for Quality in the Constructed Project"[2] points to the fact that "25% of failures resulted from poor communication or lack of coordination among the project team.".

Acceptance of the fundamental importance of human factors has been accelerated by several major changes in professional practice. These include: changes in the number and variety of participants in the design and construction process including additional sub-contractors and project managers; increased size and complexity of civil works which increases the need for group decision making; societal changes that imply new responsibilities for the parties involved together with important changes in liability; and, the

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growth of repair and renovation projects which involve a great deal of uncertainty. At the same time, significant advances in related non-engineering disciplines such as cognitive psychology, organizational theory, motivational theory and human factors have been made.

In structural engineering, the role of human factors in failures of built facilities has been recognized in several recent studies; some work has also been done in geotechnical engineering [3]. Most research to date has focused on human error and error proneness in design tasks and its control [e.g.,4, 5]. Several studies of errors in structural design including limited attempts to model human errors within the body of reliability analysis have been published. There has, however, been little effort in civil engineering to incorporate other important elements such as communications and organizational theory. These factors have contributed significantly to numerous historical failures including the Union Square collapse, the Hyatt Regency Hotel failure, the Vajont slide catastrophe, and the failure of Teton dam.

In this paper, selected aspects of the literature dealing with human factors are summarized first, with emphasis on communication and organization theory. Then, their relevance to foundation engineering tasks from site investigation to the analysis of failures is discussed, making frequent use of case histories. Hopefully, the increased awareness of important developments in fields related to human factors will stimulate efforts to control their effects in engineering practice.

HUMAN FACTORS - ORGANIZATIONS AND COMMUNICATIONS

In the general fields of cognitive psychology, motivation theory, information and communication theory and organizational behavior, many studies of potential relevance to foundation engineering have been completed. These studies attempt to characterize individuals and their interactions so as to define the forces that shape organizations. Based on a review of this literature, the following summary observations can be made.

Biases and Limitations in Decision Making. Many authors in the field of cognitive psychology have studied biases and limitations in human decision making [e.g. 6]. In general, a simple model such as that shown in Fig. 1 has been used.

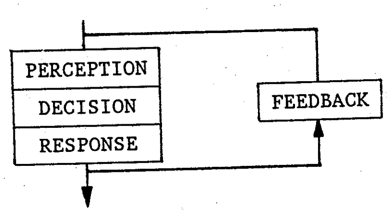

Figure 1. Stages in Decision Making

An individual's perception of information is known to depend on his preconceptions. The "see what you expect to see" phenomena is well known to us all. Selectivity in perception obviously limits the information available for decision. Perception is sensitive to the quantity of data as well as to the quality and format used in presenting the data.

Biases in decision include the misuse of so-called "heuristics" which are unconscious rules used in simplifying problems. Individuals also have a variety of personal limitations such as poor intuitive statistical capabilities, a-priori commitments to particular conclusions, and limited individual capacity.

An individual's decision process is tuned based on the outcome of previous decisions; this is a performance feedback loop. A dangerous and widely observed bias is to limit feedback to those cases that were successful. It is always tempting to attribute success to one's capabilities and failures to chance.

Communications. Miller [7] suggested that "a large part of behavior is concerned with sending, transmitting or receiving messages." Although it is an essential aspect of human life, every individual experiences difficulties in communication. This has motivated a great deal of research and the beginning of a new field that goes back to the work by Shanon and Weaver and more recently to H. Simon.

Communication implies adjusting attitudes and understandings - not just transferring information. It requires common interest and continuous feedback (Fig. 2). Failure to communicate in a real sense has contributed to many major historical events including international military conflicts and political scandals. There is no doubt that these factors have led to civil engineering accidents and to poor performance of completed works.

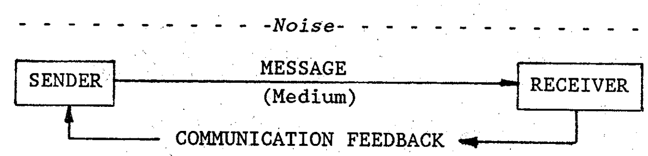

Figure 2. Schematic Representation of Communication

While a message is a stimulus that triggers meaningful responses in a receiver, it is not meaningful in itself. Feedback in communication permits the adjustment of understandings and attitudes, establishing points of agreement and disagreement.

Concepts can not be communicated unless they are understood, therefore, education is required to develop an informed, similar attitude of mind among participants [8]. Education not only improves understanding but also helps to minimize situations where poor communications result from unstated assumptions, incompatible schemes and other unconscious mechanisms.

Even if optimal conditions develop, inherent difficulties in communications will remain and special arrangements must be made to minimize their effects. Primary problems are: (a) information overload; and (b) distraction and noise, including the effects of environmental stresses and internal stresses in either a sender or a receiver.

Communications Within Organizations. Difficulties in human communication together with inherent human characteristics have particular consequences and manifestations in any organizational structure [9]. Some well documented observations [e.g., 10, 11] include: (a) communication networks increase in effectiveness as the relationships among individuals become more stable; (b) vertical communication tends to be slow; (c) horizontal and diagonal communication are hindered by self interest or inter-branch conflict; and, (d) the vast majority of all communication in large organizations is subformal.

Besides the distortion of information by limitations in the "sender - medium - receiver" chain, information within organizations is also distorted by the self interest of individuals. In particular, unfavorable information is often forgotten; when it is communicated, it is often rejected and sent back [12].

Individuals who originate disturbing information tend to be considered "trouble makers" and may be isolated or reorganized out of existence. As a result, information passed upwards in a hierarchy tends to be distorted so as to more closely reflect what senior officials would like to hear. Thus information is exaggerated if it favors a senior individual and minimized if it does not [13]. It should also be noted that, since information affects prestige and power, one must expect conscious distortions and filtering of information. Only a firmly embedded common objective can minimize intentional distortion.

Many people systematically employ counter biasing to compensate for distorted information. Whenever possible they reduce their reliance on information and use multiple sources. Information overload can significantly reduce the rate of message handling. An organization may react by filtering information or adding assistants, but these may lead to greater distortion, more omissions, and a degrading cyclic condition [13]

Communication Among Organizations. Civil engineering projects are affected not only by communications within organizations but also by communications between clients, designers, project managers, contractors and a variety of ancillary organizations such as lawyers, material suppliers, etc. The relationships between the primary organizations in a basic project are suggested in Figure 3.

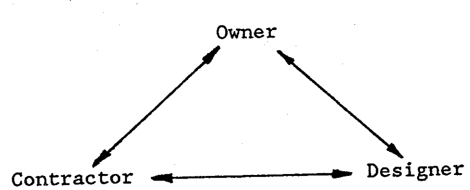

Figure 3. The Civil Engineering Project

Patterns of communication have changed in recent years as the economic, social and legal environment of civil engineering has evolved [14]. Classical, straightforward communication between clients, contractors and engineers now includes increased governmental control, risk management programs, increased participation in decision processes by other parties, and peer reviews at several stages. If damage occurs, third parties and the legal system soon become parts of the organizational structure.

One can consider the primary players as members of an upper organization with several communication links, immersed in a complex environment. In this case, the filtering and the distortion of information result from a combination of responsibilities, overlapping hierarchies of formal authorities, self-serving interests, institutional pride and commitment, and other inherent limitations. This setting is characteristic of the construction industry, and to the authors' knowledge, there has been no in-depth study of this situation.

Group Decision Making. There are many reasons to promote group decision making: e.g. collective intelligence; the pooling of information; consideration of a larger number of approaches; broader acceptance of decisions; and, the sharing of responsibility under uncertain conditions. In civil engineering, important advantages can result if individuals and companies group together to tackle complex projects.

Unfortunately, the "quality" of decisions reached by groups does not always surpass the quality of decisions made by an individual. Creativity is generally attributed to individuals although group effects are also found. Biases limiting group decision making include [e.g., 15]:

- Use of only that information which has been obtained and perceived as important.
- A lack of agreement on the essence of a problem.
- "Group-think" where individuals seeking agreement do not realistically consider all alternatives.
- The influence of high status individuals, or individual domination based on a higher degree of participation, persuasive ability or persistence.
- The passive acceptance of atypical information.
- Amplification of dominant initial tendencies. Information which confirms the majority's initial position is more likely to be accepted than other information.

Subformal Communication: On site-decisions. Civil engineering projects are characterized by uncertain field conditions and specifications that are often open to interpretation. One of the most interesting challenges in construction is to resolve daily difficulties and to make decisions involving on-site modifications of variable importance so as to complete the project on time and within budget. Such decisions are made by individuals or by small groups with subformal, primarily horizontal communication.

On-site decisions must take into consideration many variables such as constructability, time delays and additional costs. It is not surprising that decisions tend to avoid detailed analysis, "hoping for the best" and perhaps departing from the original design philosophy.

There is evidence that ad-hoc decisions are an important source of failures. However, the nature of these decisions and their effects have not been studied in detail.

FOUNDATION ENGINEERING TASKS - CASES

The previous section presented relevant human factors, emphasizing the characteristics of interactions between individuals. This section examines foundation engineering tasks from a human factors perspective, starting with site investigation, followed by the selection of foundation type, the construction and repair of facilities, the monitoring of performance and the analysis of failures.

Foundation engineering is still an art even though there is now an extensive body of scientific material available. It is at the interface between an uncertainly known geology and a structure to be built. Foundation engineers must rely on their expertise and interact not only with owners but also with designers and contractors. They must be aware of neighboring structures, and environmental restrictions, as well as new theories, materials, and construction procedures. These conditions characterize situations where human factors often play a decisive role.

Site Investigation. Site investigation involves circularity in knowledge: preliminary information about in-situ conditions, the structure to be built and the construction procedure are needed to plan the site investigation. In turn, results from the site investigation will be in-situ characteristics that determine the foundation for the structure (and maybe other structural features), as well as construction procedures. This, like other situations involving an information loop, is sensitive to incorrect initial assumptions and engineering preconceptions of the geology at the site- a clear example of potential bias in perception.

One of the most difficult aspects of site investigation is to decide how much is enough. Several attempts have been made to provide decision support tools to aid engineers in this task, e.g. Bayesian probabilities [16]. The underlying assumption is that individuals do not update uncertainty correctly because of a well documented observation called "conservatism" in the cognitive literature [see 6]. To the authors' knowledge, none of these aids has been widely adopted.

In many practical situations, limited site investigation is compensated by safer and more expensive foundations. This trade-off is sometimes used to avoid discouraging owners, who may not appreciate the importance of adequate site investigation. In this case, self-serving distortion of information among the parties may result in non-optimal decision making.

Site investigation is usually the first major expenditure in a project indicating the owner's real interest in the facility. This produces a level of commitment seldom recognized. The more money spent, the higher the drive to complete the project. In the case of major facilities, this underlying effect of site investigation may have important consequences. The failure of Teton Dam can be traced to this early stage [17]

Selection of Foundation Type The selection of a foundation type is not an easy task. For example, once a foundation engineer decides that a deep foundation is needed, he must select the type of pile from among 150 patented systems in the USA. They differ in material, length, load capacity, environmental impact, certainty of execution, etc. Because of limitations in decision making, only a few alternatives can be considered, thereby reducing the likelihood of selecting the best alternative.

To simplify decision and reduce legal risk, both site investigation and the selection of foundation type are strongly influenced by local, "common" practice. However, this attitude may overlook new developments or the changing of geological conditions in an area. As noted previously, tuning decision processes on the basis of previous positive outcomes does not necessarily lead to the development of expertise or to the selection of optimal solutions.

Construction. Organization and communication problems are particularly important during construction. Teton Dam is a very appropriate case history to show the effect of these human factors. It was designed and constructed under the supervision of one of the most renowned dam building organizations in the world - The Bureau of Reclamation.

Sherard suggested that organizational problems were the primary causes of the failure [18]. Among others, he identified the following organization and communication factors.

- Separation between design and inspection groups.
- The designers never visited the site; as a result they were "sheltered from problems and experience".
- Cooperation between the field inspection and the design team was not encouraged and was held to a minimum.
- Field engineers were assumed to have the capacity to solve problems during construction.
- Frequent questions by a field engineer to the designers was considered to have a negative impact on his record.
- The design organization did not have a qualified review team with veto power to challenge designs (independent consultants were not used)

Sherard concluded that these organizational problems created an environment that resulted in a design far short of the state of the art.

This case history is an excellent example of the potential danger of subformal communication and on-site decisions. The USBR inspection group decided to stop grouting the cracked abutments without the approval of the design engineers. Sherard indicates that grouting was stopped "because the embankment construction was going very rapidly and delays created by this gravity grouting, which was not part of the contract, were an item of significant controversy with the contractor". Unfortunately, questionable practices are not frequently reported- the threat of being discredited, a concern for the consequences, self esteem and self image are some of the factors that discourage "whistleblowing".

One modern approach to error avoidance during construction is to couple multiple levels of responsibility with the wholesale distribution of documents. Duplicate inspection, redundant information flow and the blurring of lines of authority can seriously reduce efficiency in the construction process without improving the safety of the built structure. Bureaucratic policies frustrate individuals, encourage inattention and can mask inferior performance.

Existing Foundations - Repairs. Establishing the reliability of existing structures is a complicated and uncertain task. Practice is now based on subjective data from expert inspectors and designers - an approach that involves all of the limitations and biases in decision making outlined previously.

The decision most affected by human factors is whether to repair or replace a structure. In general, the more important the structure, the more non-technical factors are involved. In major projects, such those involving the bridges in New York City, politics plays a decisive role. As another example, many jetty driven piles in the foundation of a port in Seattle were found damaged soon after the project was completed. Since the damage attracted the news media during an election, the area around the piles was simply grouted to hide the problem [19].

Monitoring. The observational method [20] permits construction when initial uncertainties are too great for normal design, and allows the completion of jobs where unexpected circumstances develop. The method is not easy to implement and the risks involved with its use are not widely recognized. It requires (1) a sufficiently clear perception of the phenomenon to select the quantities to be observed and the alternative courses of action, and (2) the insight and determination to decide when those actions must be implemented.

The Vajont Dam slide can be discussed in this context because of the extensive monitoring program that was undertaken. The 276 m double arched dam was built to impound the Vajont river in northern Italy. During construction, signs of movement of the left side were observed and an inspection/monitoring program was begun. A careful model was conducted to predict the size of the wave that could take place: results indicated a maximum wave height of 26 m. The slide which took place on October 9, 1963, formed a 200 m high wave that destroyed villages downstream. More than 2000 lives were lost including the personnel monitoring the dam and their families (45 engineers and technicians). Possibly, incorrect model results mislead decision makers.

The most important causes of the catastrophe were misperceptions of the phenomenon, errors in judgment, and incorrect assumptions. However, records indicate other important factors [21]:

- Expertise was dispersed with poor communication links.
- The "I must be wrong" syndrome when one disagrees with famous experts was in evidence.
- Experts were committed to their initial assessments, refusing to accept what others accepted and ignoring contradictory evidence.
- Sources of unfavorable information were removed.
- Authorities were hesitant to take drastic measures even when signs of distress were obvious. Two or three days before the slide, velocities were 6 times higher than ever before, noises were heard and stones fell. Although phone calls were made, the population was not evacuated.
- Responsibilities were very poorly defined [22].

Monitoring systems -and site investigation- can soon produce more information than can adequately be handled by an individual or even a team. If the processing of the information is not planned in advance, a great deal of effort may be wasted. Adequate data presentation based on well established ergonomic principles are as important in geotechnical engineering as they are in computerized war cruisers and nuclear power plants.

Analysis of Failures. The difficulty of the a-posteriori analysis of failures is demonstrated by Teton Dam. A costly post failure investigation and numerous additional studies were performed by some of the most prestigious geotechnical engineers in the world including Casagrande, Chadwick, Peck, Seed and Sherard. However, 14 years after its failure, the cause of the failure or the "triggering mechanism" remains controversial.

Many use an inductive approach to the analysis of failures, building confidence in a potential triggering mechanism as confirming evidence is found. Because of the complexity of natural phenomena, it is possible in most cases to obtain data that fits one's expectations. A more rigorous and less biased approach must be based on a real attempt to falsify hypotheses instead of validating them. Leonards method for the analysis of failures is based on these premises [23].

A preconception of a problem is required to guide the gathering of information. However these a-priori views affect the perception of the information and its posterior analysis. In addition, because of bias in decision making and distortion of information in organizational hierarchies, it is not surprising that consultants retained by an involved party will tend to support its position.

This was the case of the foundation failure of the oil tank, 79.3 m in diameter and 19.5 m high, at Falley -England [24]. Data compiled by Leonards [25] is presented in Table 1; none of the consultants concluded against the party they worked for.

Another common bias takes place in the back analysis of failed slopes. Because of the complexity of any system and the simplicity of any analytical model, it is unlikely that the calculated factor of safety will be 1.0. However the geotechnical literature includes numerous analyses that show a FS= 1.0 for failed slopes. Such misleading results can only create a false sense of confidence and slow the learning process in the field. The variability of results in prediction exercises, on the other hand, always surprise the profession.

Table 1. Consultants' Bias To Their Retainers [25]

PARTY	CONSULTANTS	CONCLUSION
Owner (EXXON)	Several Consultants	Bad piles Against Contractor
Piling Contractor (ALPHAPILE)	Several Consultants	Bad Ground Against Owner
Geotechnical Consult/Design (Laing)	Several Consultants	Bad Ground Against Owner

Finally, biased perception of feedback may occur in the extreme case that all foundation designs were successful. In this case, an individual (or the profession) should not become overconfident of the adequacy of his decisions but should question whether this was the result of over conservative designs. R.F. Scott [26] recognized this problem in his Rankine Lecture: "Little is learned from an unfailed dam. Are not more failures needed ... in field and model tests, to which analyses can be applied, to ensure that too much money is not being spent unnecessarily?".

FINAL COMMENTS

Several suggestions to limit the effects of human factors in design and construction practice can be put forward. These include:

- Changes in the structure of project organizations through, for example, different contractual arrangements.
- Improvements in the training of key personnel by, for example, sensitizing individuals to the phenomena involved through the study of case histories.
- Development of computerized decision support tools and communication systems with in depth knowledge of human factors to complement individuals.

Innovative applications of computers are being developed including expert systems, intelligent information retrieval, management information systems, distributed artificial intelligence, computerized performance monitoring, networking and specialized computer mediated communication. However, automated computer implementations are not yet mature, and the possibility of "deadlocks" and complex systems that "break loose" until errors are found is of great concern (e.g., computerized trading).

Parallel to all these technological developments, is a renewed interest in improvements in engineering education. Following practices in other professions such as law and medicine, it has been suggested that the study of a large number of cases is one of the most efficient approaches to the development of expertise [5, 27].

Awareness, responsibility, reduced bureaucracy and real common interest are essential to effective communication.

Smith [28] concluded an analysis of bridge failures with the following remarks: "Behind every engineering mistake there must lie a human engineer who makes it, either alone or through lack of team cohesion. From a reading of many reports it is clear that a happy, close-knit team is a strong safeguard against both design error and failure during construction. There can be no infallible method of building such a team. It starts with a good engineer/client relationship, and it involves a formally defined sharing of responsibilities which are well understood and accepted by all concerned, backed by personal warmth and mutual helpfulness. A change in the team during the course of the work is a step fraught with danger, to be taken only for the strongest reasons, and to be followed by a thorough and time-consuming review of the work plan and the team relationships." Findings in human factor research support all these observations.

This overview has presented a summary of cognitive and communicative characteristics in individuals and their effect on organizations. The cases discussed demonstrate that these factors are critically linked to the performance of built facilities.

A number of issues warrant special attention and need further research. These include the role of subformal communications, the effect of on-site decisions, and the profound effect of biases in information loops such as in site investigation, monitoring, and in the analysis of failures.

REFERENCES

1. House Committee on Science and Technology, Structural Failures in Public Facilities, U.S. Gov.Print.Off., Washington, D.C., Mar 1984.
2. ASCE, Quality in the Construction Project - A Guideline for Owners, Designers and Constructors, Manual of Professional Practice(ASCE), New York, 1988, 192 p.
3. JC Santamarina & JL Chameau, Limitations in Decision Making and System Performance, J.Perf.Const.Fac.(ASCE), in print, 1989.
4. RE Melchers & co-workers, Research on Human Error in Design Tasks, Series of Reports starting in 1982, Monash University, Australia.
5. CJ Turkstra, Human and Organizational Aspects, Theme Paper, Proc IABSE Symposium, Tokyo, 1986, 97-106.
6. RM Hogarth, Judgment and Choice The Psychology of Decision, Wiley, New York, 1980, 250p.
7. GA Miller, The Psychology of Communication, Basic Books, New York, 1967, 197p.
8. J Parry, The Psychology of Human Communication, Elsevier, New York, 1968, 284p.
9. F Jablin, L Putnoon, K Coberts, & L Porter, - Eds, Handbook of Organizational Communication, Sage, Beverly Hills, 1987, 781p.
10. A Downs, Inside Bureaucracy, Little, Brown and Company, 1967, 292p.

11. MB Lee & WL Zwerman, Development a Facilitation System for Horizontal and Diagonal Communication in Organizations, INTERCOM, Readings in Organizational Communication, Ed S Ferguson & SD Ferguson, Hayden, Roshelle Park, 1980, 412p.
12. DA Bella, Organizations and Systematic Distortion of Information, J.Prof.Iss.Eng.(ASCE), 113(4), 1987, 360-370.
13. S Ferguson & SD Ferguson, Assessing Information Load, in INTERCOM, Readings in Organizational Communication, Ferguson & Ferguson Eds., Hayden, Roshelle Park, 1980, 412p.
14. DC Moorhouse, The Movement Toward a Risk-Free Society: A Consulting Engineer's Perspective, Geotech.News, Mar 1987, 20-23.
15. DS Gouran & RY Hirokawa, Counteractive Functions of Communication in Effective Group Decision Making, Communication and Group Decision Making, Ed RY Hirokawa & MS Poole, Sage, Beverly Hills, 1986, 315p.
16. CJ Turkstra, Applications of Bayesian Decision Theory, S.M. Study No. 2., University of Waterloo, 1970, 49-71.
17. DJ Duck, RW Kramer & LW Davidson, Teton Dam: Summary of Technical Investigations, USBR, Presented at the 13th ICOLD, New Delhi, 1979, 41 p.
18. JL Sherard, Lessons form the Teton Dam Failure, & Teton Dam Failure - Retrospective Comments, Dam Failures, Proc.Int.Work. Purdue Univ., Ed GA Leonards, 1987, 239-256 & 283-293.
19. BH Fellinius, Personal Communication at Purdue University, Nov 11, 1986.
20. RB Peck, Advantages and Limitations of the Observational Method in Applied Soil Mechanics, Geotechnique, 19(2), 1969, 171-187.
21. L Muller, The Vajont Catastrophe - A Personal Review, Comments in Open Discussion, & Prepared Discussion, Dam Failures, Proc.Int.Work. Purdue Univ, Ed GA Leonards, 1987, 423-444, 559, & 493-512.
22. V Milligan, Closing Remarks Panel Discussion, Dam Failures, Proc.Int.Work, Purdue University, Ed GA Leonards, 1987, 572-574.
23. GA Leonards, Foundation Performance of Tower of Pisa, Discussion, J.Geot.Eng.(ASCE), 105(1), 1979, 95-105.
24. GA Leonards, Investigation of Failures, J.Geot.Eng.(ASCE), 108(2), 1981, 187-246.
25. GA Leonards, Foundation Engineering, Class notes, Civil Eng. Dep., Purdue Univ., West Lafayette.
26. RF Scott, Failure, 27th Rankine Lecture, Geotechnique, 37(4), Dec 1987, 423-466.
27. CJ Turkstra, The Case for Case Studies in Engineering Education, Modeling Human Error in Structural Design and Construction, Ed A Nowak, Ann Arbor, Jun 1986, 128-132.
28. DW Smith, Why do Bridges Fail, Civ.Eng.(ASCE), Nov 1977, 58-62.

MOVEMENT CONTROL OF EXCAVATION SUPPORT SYSTEMS BY ITERATIVE DESIGN

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ABSTRACT: Conventional design practice for excavation support systems emphasizes determination of loads and selection of structural components. However, most problems with these systems occur because of movements and the all too often accompanying litigation. This paper presents a method which uses movement control as a central focus in the design process. Before structural design is finalized or specifications are written, issues associated with potential movements of the system are resolved. To assist working within the context of the new method, procedures are presented to guide the estimation of excavation support system movements. Emphasis is placed on the fact that movements are generated as a result of the soil and structure system, as well as by the construction procedure. Case histories are used to illustrate problems that can benefit from the new approach. It is believed that the new approach is important not only because it causes a designer or contractor to determine potential movements, but also because the process forces a consideration of the effects of a wide range of variables not regularly included in design.

INTRODUCTION

The conventional approach to design of excavation support systems concentrates on choosing loads, and then obtaining component member sizes using conventional structural analysis procedures. This is typically the manner in which the process is presented in textbooks and, thus, is how our engineers are taught to think. Unfortunately, far too often, the issues of deformations of the system, and how the system construction process will affect performance are addressed only in the final stages of design, if at all. The writers would

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