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CONTENTS

DISCUSSION

Proc. Paper 11674

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TECHNICAL NOTES

Proc. Paper 11684

INFORMATION RETRIEVAL

The key words, abstract, and reference "cards" for each article in this Journal represent part of the ASCE participation in the EJC information retrieval plan. The retrieval data are placed herein so that each can be cut out, placed on a 3 × 5 card and given an accession number for the user's file. The accession number is then entered on key word cards so that the user can subsequently match key words to choose the articles he wishes. Details of this program were given in an August, 1962 article in CIVIL ENGINEERING, reprints of which are available on request to ASCE headquarters.

[a]Discussion period closed for this paper. Any other discussion received during this discussion period will be published in subsequent Journals.

11697 SEISMIC INSTRUMENTATION OF DAMS

KEY WORDS: Accelerometers; Dams; Dynamics; **Earthquakes; Geotechnical engineering; Instrumentation; Seismic detection; Seismographs**

ABSTRACT: The desirability of installing seismic instruments on and near major dams is explained. Two types of instruments are required: (1) Strong-motion accelerographs for recording potentially destructive ground shaking and resulting dam vibrations; and (2) sensitive seismographs for determining the local seismicity. A minimum of two strong-motion accelerographs should be installed on the dam and a minimum of two should be installed in the immediate vicinity of the dam. Each accelerograph should record three components of motion, should have a natural frequency of approx. 20 Hz, a recording speed of approx 1 cm/s. The sensitive seismographs are intended to record the local seismicity in the vicinity of the dam site before construction, and to detect any changes in seismicity during reservoir filling. A minimum of three seismographs is recommended for installation in the vicinity of the dam site. A vertical-component seismometer (1 Hz - 5 Hz) with visual recorder and approx 10,000 magnification at 1 Hz is recommended.

REFERENCE: Bolt, Bruce A., and Hudson, Donald E., "Seismic Instrumentation of Dams," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT11, **Proc. Paper 11697**, November, 1975, pp. 1095-1104

11705 END EFFECTS ON STABILITY OF COHESIVE SLOPES

KEY WORDS: Boundary conditions; **Cohesive soils;** Equilibrium; Failure; **Geotechnical engineering;** Safety factor; **Slopes; Slope stability; Stability analysis**

ABSTRACT: The concept of the "two-dimensional" circular arc method of stability analysis is extended to three-dimensional slope stability problems. End effects on the stability of cohesive slopes due to failure along a finite length are evaluated by means of a computer program STAB3D developed for this purpose. As an application of the technique, two cases are considered: (1) The toe failure of a vertical cut where typical end effects are illustrated; and (2) the toe failure of a slope with any angle β when a finite length of failure is imposed. The stability of a test section embankment loaded to failure is analyzed.

REFERENCE: Baligh, Mohsen M., and Azzouz, Amr S., "End Effects on Stability of Cohesive Slopes," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT11, **Proc. Paper 11705**, November, 1975, pp. 1105-1117

11706 QUASI-STATIC DEEP PENETRATION IN CLAYS

KEY WORDS: **Clays;** Cones; Deformation; **Geotechnical engineering; Penetration; Penetration resistance;** Steady state; Strain tests; **Wedges**

ABSTRACT: Deformations caused by the steady-state penetration of a rigid rough wedge in clay are compared with theoretical predictions. It is found that the mechanism of sharp wedge penetration was consistent with the cutting process assumed by the theory. However, the larger the apex wedge angle the less accurate are the theoretical predictions. The mechanism of blunt wedge penetration is one of compression in which a rigid region of clay moves with the wedge, so that the deformation patterns are difficult to interpret. Measured penetration resistance is in reasonable agreement with the theory. The suitability of plasticity theory to resolve penetration problems is assessed and its deficiencies identified.

REFERENCE: Baligh, Mohsen M., and Scott, Ronald F., "Quasi-Static Deep Penetration in Clays," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT11, **Proc. Paper 11706**, November, 1975, pp. 1119-1133

U.S. Customary-SI Conversion Factors

In accordance with the October, 1970 action of the ASCE Board of Direction, which stated that all publications of the Society should list all measurements in both U.S. Customary and SI (International System) units, the following list contains conversion factors to enable readers to compute the SI unit values of measurements. A complete guide to the SI system and its use has been published by the American Society for Testing and Materials. Copies of this publication (ASTM E-380) can be purchased from ASCE at a price of 75¢ each; orders must be prepaid.

All authors of *Journal* papers are being asked to prepare their papers in this dual-unit format. Until this practice affects the majority of papers published, we will continue to print this table of conversion factors:

To convert	To	Multiply by
inches (in.)	millimeters (mm)	25.40
inches (in.)	centimeters (cm)	2.540
inches (in.)	meters (m)	0.0254
feet (ft)	meters (m)	0.305
miles (miles)	kilometers (km)	1.61
yards (yd)	meters (m)	0.91
square inches (sq in.)	square centimeters (cm²)	6.45
square feet (sq ft)	square meters (m²)	0.093
square yards (sq yd)	square meters (m²)	0.836
acres (acre)	square meters (m²)	4047
square miles (sq miles)	square kilometers (km²)	2.59
cubic inches (cu in.)	cubic centimeters (cm³)	16.4
cubic feet (cu ft)	cubic meters (m³)	0.028
cubic yards (cu yd)	cubic meters (m³)	0.765
pounds (lb)	kilograms (kg)	0.453
tons (ton)	kilograms (kg)	907.2
one pound force (lbf)	newtons (N)	4.45
one kilogram force (kgf)	newtons (N)	9.81
pounds per square foot (psf)	newtons per square meter (N/m²)	47.9
pounds per square inch (psi)	kilonewtons per square meter (kN/m²)	6.9
gallons (gal)	cubic meters (m³)	0.0038
acre-feet (acre-ft)	cubic meters (m³)	1233
gallons per minute (gal/min)	cubic meters per minute (m³/min)	0.0038
newtons per square meter (N/m²)	pascals (Pa)	1.00

JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION

Seismic Instrumentation of Dams

By Bruce A. Bolt[1] and Donald E. Hudson[2]

Introduction

A large earth or concrete dam represents a notably important type of seismic hazard evaluation problem. Not only is the dam in itself a relatively expensive project, but it is intimately involved in the whole economy, through power generation, flood control, irrigation, etc. In addition, structural failure of a dam may lead to a major disaster because large populations may be exposed to sudden flooding.

A number of examples could be cited of major damage to earth dams by "natural" earthquakes, e.g., Hebgen Dam in Montana (12), the Eklutna Dam in Alaska (11), and the lower Van Norman Dam in California (13). Many large dams around the world are located in highly seismic regions, close to areas that have in the past suffered major earthquakes. The likelihood of future damaging shocks must always be kept in mind.

In addition to the danger from natural earthquakes, several examples have now occurred in different countries of damaging earthquakes apparently related in some way to reservoir loading behind the dam (6,10). Some of these examples have occurred in regions that had not been thought to be even moderately seismic. Thus, risk from induced seismicity must, for the time being, be considered for all proposed large dams. The three clearest cases are: (1) Lake Kariba in Central Africa, the world's largest artificial reservoir; (2) Koyna in India; and (3) Hsinfengkiang in the People's Republic of China. In these examples, the largest shocks reached magnitude 6.4. At Koyna, in addition to significant cracking of the concrete gravity dam which required a major repair and strengthening operation, numerous collapsed houses in the vicinity caused a large loss of life (2,5). Hsinfengkiang Dam, which is located in an essentially aseismic region, impounded a reservoir which, subsequent to 1959, was the site of numerous small shallow earthquakes (4). The principal shock in 1962

Note.—Discussion open until April 1, 1976. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 101, No. GT11, November, 1975.

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had magnitude 6.1 and produced a crack 82 m long in the upper concrete dam structure.

To study either earthquake damage or reservoir-induced seismicity, it is essential that instrumentation be installed prior to the event. Only the seismographic instrumentation will be presented herein. However, where feasible and warranted by the dam size and location, attention should also be given to preconstruction geodetic surveys of the region for purposes of detecting changes in crustal deformations associated with reservoir loading, and to the installation of hydrographs for measuring large excursions of water wave motion (seiches) in the reservoir.

In the absence of suitable recording instruments to measure the severity of earthquake ground motions and of the dam response, the occurrence of a strong earthquake will pose many questions that cannot be answered. If structural damage has occurred, there is no way without the measurements to compare behavior with design earthquake conditions, to estimate performance for other, perhaps larger shocks, or to make rational design decisions for repair and strengthening of the structure. If no obvious damage has occurred, it is difficult without measurements to decide on the extent to which elaborate and expensive inspection operations should be carried out.

As far as induced earthquakes from reservoir-loading are concerned, a network of seismographs adequate for the approximate location of small local earthquakes must be in operation before the impounding of the reservoir (9). Without such a network it is usually impossible to establish the seismicity of the area prior to closure. Thus the extent to which local earthquakes were a consequence of the reservoir, or were part of a more general seismic pattern, cannot be decided. Such a decision is essential to an evaluation of the probable size and location of future shocks, and thus is of immediate practical importance.

The purpose herein is to recommend minimum instrument requirements to cover the two types of earthquake problems mentioned. Since different types of measurement are required for the two situations, the subject will be treated under the headings: (1) Strong-motion instrumentation; and (2) local seismograph networks.

Basic Principles Behind Recommendations

For many large dams, the seriousness of the earthquake hazard and the overall importance of the project will be such that a very extensive instrumentation program under the direction of expert consultants will normally be involved. Such projects go far beyond the scope of the present document, which aims only at establishing certain minimum standards which can be recommended for all major dams at a high level of justification. Experience so far suggests that reservoir-induced seismicity is associated with dams approx 100 high or taller. Smaller dams, however, may have a high disaster potential. This suggests that the local seismograph network could be limited to high dams, but the strong-motion instrumentation, should be included for lower dams as well if danger to populations is involved.

The scope of the present recommendations sets definite constraints on the elaborateness of the instrumental systems, which have deliberately aimed at simplicity and reliability. Some general principles are:

1. An earthquake is an experiment that can never be exactly repeated. Furthermore, moderately large earthquakes are fortunately rare occurrences, so that opportunities for direct measurement are infrequent. This means that the ultimate in reliability must be aimed at. This in turn requires instruments of a basic simplicity which have been thoroughly field tested over a period of years. For these reasons, specific instrumentation recommended is of a relatively simple time-tested type, far from representing the ultimate data-collection capability. Even for projects that can be directed by experienced instrumentation experts and have the resources for the most elaborate modern equipment, addition of the recommended basic instrumentation would be good practice.

As more elaborate instrumentation (e.g., force-balance transducers, central recording systems, and direct digital systems) acquires a suitable background of field testing and achieves an adequate level of reliability, the present recommendations should be revised and updated.

2. It is assumed that many dams will be in regions in which highly trained instrument technicians and seismologists will not be available on a permanent or even a temporary basis. For this reason, the recommended instrumentation is of a type which can be installed, operated, and maintained by reasonably competent nonspecialist technicians with a minimum amount of direction. Similarly, it is supposed that the output information should be in such a form that local judgments of the importance of specific recordings can be made. Provisions for more detailed data analysis, usually available from a number of sources, should be made if warranted by the observations.

3. It is assumed that the recommendations should be sufficiently specific so that satisfactory commercially available equipment can be selected and acquired without the need for consultation which instrumentation specialists. Such consultation will naturally be required for more elaborate studies, but for the minimum recommended system suitable instrument types are now sufficiently well defined to come within standard equipment procurement policy.

It will readily be understood that the basic assumptions just mentioned severely limit the scope of the recommendations, and will explain the highly conservative nature of the approach.

Strong-Motion Instrumentation

Instrument Characteristics.—The first requirement for strong-motion instrumentation is insensitivity—the strongest possible earthquake ground motions should stay on scale. In addition, a wide dynamic range is advantageous, since valuable information can be obtained from small nondamaging earthquakes. To study the dynamic response of the dam, a wide frequency response range is also required. This implies high recording speeds that make continuous recording impracticable. An inertia trigger operated by the initial portion of the earthquake ground motion has been found to be a satisfactory solution to this problem.

The only commercially available thoroughly tested instruments having the previous special characteristics are so-called "strong-motion accelerographs" (7,8). The recommended characteristics of a strong-motion accelerograph (Fig. 1) suitable for the present purpose are:

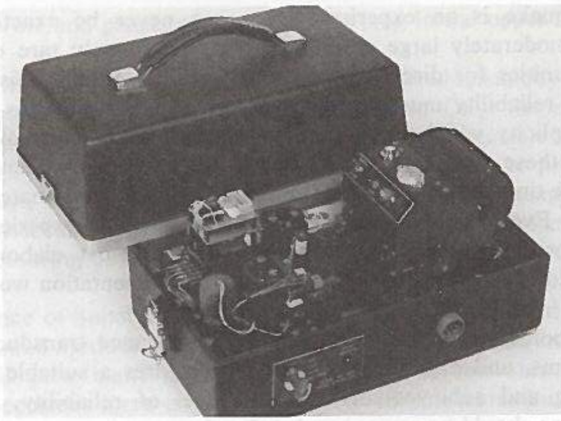

FIG. 1.—Type SMA-1 Strong Motion Accelerograph with Case (approx 36 cm long), 70-mm Film Drive; Three Orthogonal Accelerometer Transducers; One Vertical Electromagnetic Starter; Trickle-Chargeable Storage Battery

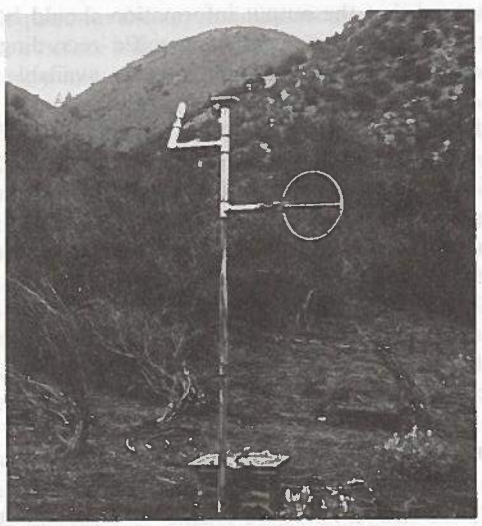

FIG. 2.—Unattended Field Installation of Strong Motion Accelerograph [Vertical Pole Supports Circular Loop Antenna for Time Signals (Right) and Two Solar Cells for Charging Batteries; Protective Housing Contains SMA-1 Accelerograph; Radio Receiver; and Power Batteries Supply; and Pole (approx 3m high)]

1. Three-component transducer of: 15 Hz–25 Hz natural frequency and 60%–70% critical damping.
2. Mechanical-optical-photographic magnitification and recording: 70-mm film or 12-in. paper preferred; 35-mm film acceptable.
3. Recording speed: ≥ 1 cm/s.

4. Recording time: Approx 30 min total—automatic reset for at least five events.
5. Full-scale acceleration level: ≥ 1*g*.
6. Acceleration resolution: 0.001*g* (dynamic range = 1,000).
7. Inertia starter: Trigger on vertical acceleration, at adjustable levels ≥ 0.01*g*. Time to full operation ≤0.1 sec. High frequency cut-off filter at approx 10 Hz.
8. Timing trace, with internal time generation, two marks per second accuracy ±0.2%.
9. Fixed trace, for baseline adjustments.
10. Battery power, with trickle charger from mains or solar cells (Fig. 2).

Accelerograph Location.—Completely adequate definition of input ground motions and dam response would require a large number of accelerographs at carefully selected points. For major dam projects, in highly seismic regions, detailed studies of the optimum number and location of accelerographs would be expected for the special conditions of the particular site. For minimum recommendations, however, questions of location are secondary to the prime object of ensuring that at least some information of engineering value will be obtained for all strong shaking.

For this purpose, it is recommended that not less than four strong-motion accelerographs be installed. Two of these should be located to record earthquake motions in the foundation, and two to measure dam response. The foundation instruments can often be mounted on dam abutments, or at an appropriate site in the immediate vicinity of the dam that is not obviously influenced in a major way by local geologic structural features. The instruments to measure dam response can usually be mounted at two different locations on the crest, or in upper galleries should they exist, avoiding special superstructures which may introduce localized dynamic behavior.

The purpose of requiring two instruments for each function is to give some indication of the uniformity of conditions, and to ensure some useful information in the event of instrument malfunction.

Accelerograph Installation and Maintenance.—It is essential that the instruments be well protected from such environmental conditions as flooding or excessive summer temperatures, and from tampering or vandalism. The accelerograph, which is of the order of 20 cm × 20 cm × 40 cm in size, can often be conveniently installed in the corner of a small structure, such as an office, instrument room, or storage room, or in a gallery of the dam. If no structure of this type is available near a suitable site, an insulated metal enclosure sealed against weather and interference can usually be provided by the instrument manufacturer at a reasonable cost.

The accelerograph should be firmly bolted down to a concrete foundation, following the instructions of the instrument manufacturer. If a suitable concrete floor is not available, a concrete pad, somewhat larger than the instrument base and of the order of 20 cm–30 cm thick will suffice. This pad should be tied securely into the foundation rock. Accelerograph installation can usually be satisfactorily accomplished by nonspecialist technicians on the regular staff of the dam.

Checking, maintenance, and servicing of the accelerographs should be carried out on a regular schedule according to the instructions of the instrument manufacturer. Routine maintenance can usually be carried out by a regular member of the dam technical staff, with a small amount of special training. In the same way, instructions can be given for the retrieval of records after an earthquake, with proper preservation and transmittal for data processing.

Accelerograph Cost Estimates.—Accelerographs meeting the prior requirements are commercially available at 1974 prices in the \$1,500-\$2,500 range. A suitable protective housing can usually be provided, if necessary, for \$500-\$1,000. The only additional cost of installation will be the provision of standard electric lines or solar panels for battery trickle charging. The total 1974 cost of a typical recommended system will thus be of the order of \$10,000.

Local Seismograph Networks

Network Requirements.—Sensitive seismographs to measure local earthquakes should be placed in the vicinity of the dam before major construction begins. The purpose of such instrumentation (1,3) is to: (1) Determine the frequency of local earthquakes (if any); (2) determine the location of seismic activity and its depth; (3) determine the magnitude and some indication of focal mechanisms of the earthquakes; and (4) allow prediction of the course of earthquake occurrence.

Reasonably precise location of an earthquake focus requires that the onset of P waves (and also S waves where feasible) be recorded to an accuracy of ± 0.1 sec, or better, at a minimum of four nearby seismographs. There must be a common time base for all seismographs and they should ideally surround the region of earthquake activity. The overall aims can be accomplished in two stages. In the preclosure stage, where the main purpose is to establish if any local earthquakes occur normally at all, a minimum network of three short-period vertical-component seismometers may be sufficient. With such a network a rough but adequate assessment of background earthquake frequency, location (using P and S waves), and magnitude can be made. If local earthquakes are prevalent the network should be expanded to at least four seismographs with the additional seismometer as near as possible to the active area.

After closure, it is advisable, at the least, to operate a four-station network for a period extending some years beyond the time when maximum impounding is complete. If a sequence of earthquakes does occur then the network should be densified. Such studies of reservoir induced seismicity usually warrant special research which goes beyond the scope of this document. The requirement then is to obtain an accuracy in the location of earthquake foci of about 1 km, so that correlations with geological faults can be made.

Network Location.—The selection of sites for the sensitive seismographs often depends on practical considerations such as accessibility and avoidance of construction work. However, several general considerations should govern the configuration to the greatest extent practically possible.

First, the sites should be uniformly spread in azimuth around the reservoir. The interstation distance should not exceed about 30 km or be less than 5 km. Individual site selection should depend upon the local tectonic structures. The instruments are best located on outcrops of basement rock and they should be as remote as can be achieved from construction activities, streams, quarrying, spillways, etc. Normally, sites should be chosen so that they do not have to

be shifted throughout the life of the project and reservoir impoundment. It is also helpful to make field surveys of the relative background microseismic noise at prospective sites, using a portable seismographic recorder before locations are finalized.

It has been found adequate to place the seismometers in shallow pits (about 1 m deep) in the surficial rock. A generally adequate housing is a steel drum, with a watertight cover, that is set on concrete poured at the bottom of the pit.

Seismographic Characteristics.—A variety of suitable components for a reliable high-gain seismographic system is now commercially available. Thus numerous systems can be designed to meet the aims set out previously. Two alternative schemes which meet the minimum requirement and have been field tested are suggested here. In both cases, the response of the overall seismographic system should be between 5 Hz and 50 Hz.

FIG. 3.—Single Sensitive Station of System A (Portable Seismograph Records on Smoked Paper and Contains Its Own Batteries): *(a)* Seismometer; *(b)* Radio Receiver

Seismographic System A.—The system makes use of available portable seismometers and visual recording units (Fig. 3). The network stations are not connected together and depend upon separate crystal clocks at each recorder. Recording is normally on smoked paper and the paper records must be changed every day. This can be done by a member of the dam maintenance staff without special training.

The portable system for each site is in four parts: (1) Seismometer; (2) waterproof single-packaged recording unit with batteries (size approx 50 cm × 50 cm × 25 cm); (3) radio receiver; and (4) power source such as solar battery charger.

The recommended characteristics are:

1. Vertical-component seismometer: (magnetic suspension preferable) natural frequency in range 1 Hz-5 Hz.

2. Visual recorder: 30 cm-35 cm wide paper record preferred; adjustable drum rate about 60 mm per minute; crystal clock providing time marks, accuracy 10^{-6}; and amplifier and filters to achieve at least 10,000 magnification at 1 Hz.
3. Recording time: At least 24 hr.
4. Radio receiver: Crystal-controlled; WWV or equivalent for time code on record.
5. Power: ±12 v and 30 amps.

Seismographic System B.—This system telemeters the signals from individual seismometers of the network to a central recording room by hard-wire connections often utilizing commercial telephone lines. Power is needed at the individual seismometers for the amplifiers and voltage-controlled oscillators. At the recording station, additional power is needed for the signal discriminators, amplifiers, and drum recorders. The system is more expensive than System A because of the cost of land lines. Its great advantage is the centralization of recording at one convenient accessible location. Maintenance personnel would rarely need to visit the seismometers in the field. Components of the telemetered system, all commercially available, have the following recommended characteristics:

1. Vertical-component seismometer: velocity transducer, natural frequency in range 1 Hz-5 Hz.
2. Seismometer voltage amplifier: 400,000 voltage gain in 6 dB steps; plug-in filters.
3. FM voltage-controlled oscillator: center frequency 300 Hz-3,000 Hz.
4. Field batteries: ±12 v, gelled electrolyte.
5. Solar battery charger: balanced for about 15-ma load considering weather and latitude.
6. Discriminator: compatible with center frequency and impedance of voltage controlled oscillator.
7. Amplifier: for drive of recording stylus.
8. Crystal controlled clock (one only) for hour and minute marks on seismograms.
9. Radio receiver (one only) crystal controlled, WWV or equivalent for time code on record.
10. Visual recorder: drum speed 60 mm per minute; direct writing; 30 cm-35 cm width paper record preferred.
11. Recording time: at least 24 hr.

Network Operation and Analysis.—Operation of either of the two types of network described previously should not require instrumentation specialists or a staff seismologist. The critical requirements in all such studies of seismicity are continuity of operation and minimum system adjustments.

With either system, an operator would need to change the paper records each day of the week at about the same hour. He would need to mark the seismograms carefully with date and location. Any absolutely essential changes in system characteristics would need to be logged. It may be necessary, from time to time, to readjust and calibrate the seismometers following procedures set out by the equipment manufacturers.

For the telemetry system B, the discriminators, radio, clock, and recording drums can usually be located in a small room in the dam engineering quarters. The a-c power is usually available. Seismograms can often be examined and stored in the same facility. All seismographic instrumentation should be tied down to the building structure to prevent movement and damage in the case of an earthquake.

The analysis side of the high-gain system often requires some seismological expertise. Special arrangements are not needed, of course, if no or very few local earthquakes are recorded. However, if the region is seismic or if the local seismicity increases on dam closure, or both, it is recommended that some special advice be obtained on analysis from a consultant seismologist.

Cost Estimates.—The components in the two systems previously outlined are now commonly available and widely used by seismologists. At 1974 prices the seismometers in System A cost about $900. A complete portable recording system can be obtained for $3,500. A suitable solar cell unit is about $500-$600. The total cost of a four-station network of System A type is thus about $20,000. No cost is included for preparation of pits or housing.

The cost of installation of the preferred System B is somewhat higher. The seismometer-amplifier-oscillator package at each site is listed at about $1,600 in 1974. At the central recording facility, each discriminator-amplifier-recorder package costs about $2,500. A suitable crystal clock is about $1,500 and a WWV radio receiver $500. The estimated total cost of the instrumentation at current prices is thus again about 20,000. In addition, however, there is cost of the overland telemetry lines. In some areas commercial telephone lines may be available for rental. (In certain circumstances, RF radio telemetry links may be suitable. They are not yet as thoroughly reliable, however, as the systems recommended previously.

Acknowledgments

This paper was originally prepared for the United States Committee on Large Dams (USCOLD) Committee on Earthquakes and the helpful advice received from our fellow committee members is acknowledged. The USCOLD recognizes that potentially destructive earthquakes pose special problems to the designers of dams which require continuing study and, therefore, has organized a standing Committee on Earthquakes.

Appendix I.—Utilization of Records Obtained during Earthquakes

When a strong earthquake occurs near an instrumented dam the film record should be collected from the accelerographs and should be developed. If the recorded acceleration exceeds 15% *g*, or if there is evidence of overstressing of the dam, it would be advisable to make a special study of the implications of the recorded accelerations as regards stresses and strains developed in the dam during the earthquake. If the dam was overstressed during the earthquake, the records will be of value in assessing the condition of the dam.

A file of strong motion accelerograms recorded in the United States is maintained by the Seismic Engineering Branch, U.S. Geological Survey, 390 Main Street, San Francisco, Calif., 94105. It is recommended that original accelerograms recorded in the United States be deposited at this office. Copies of the original records can then be made available for research purposes to those organizations wishing to carry out studies in depth. In other countries it would also be advisable to maintain a central file of accelerograph records.

The USCOLD Committee on Earthquakes, upon request, will provide advice on studies that should be made of accelerograms.

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JOURNAL OF THE
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End Effects on Stability of Cohesive Slopes

By Mohsen M. Baligh[1] and Amr S. Azzouz[2]

Introduction

Stability is an important consideration in the design of dams, levees, breakwaters, embankments for transportation facilities, cut slopes, and excavations. The result of a failure can be costly, involving the loss of time and property and even lives. Wright (15) presents a thorough literature survey of existing methods of slope stability analysis. Most of these methods use limit equilibrium techniques and apply to plane-strain conditions. Rigorously speaking, the plane-strain analysis implies that an embankment failure should extend for an infinite distance along its axis. Practically, a "reasonably long" failure makes the plane-strain analysis "reasonably applicable" to the observed three-dimensional failures.

However, for such problems as the stability of high dams constructed in narrow rock-walled valleys, the end effects are important and thus the problem can no longer be treated by means of the plane-strain analysis. In contrast to the voluminous literature on two-dimensional slope stability, little work has been done regarding three-dimensional problems. Sherard, et al. (9) present a method of analysis for three dimensional problems which is specifically intended to evaluate end effects for high dams in narrow valleys. This method essentially gives a "weighted" average of the stability of various sections of the embankment. The length of the dam is divided into a series of segments of equal lengths. The average cross section of each segment is analyzed as a two-dimensional problem. The factor of safety is then defined as the ratio of the sum of the resisting forces to the sum of the driving forces for all segments of dam length.

This article extends the concept of the two-dimensional circular arc shear failure method to three-dimensional slope stability problems. The techniques presented herein can be considered a more organized and rational approach of the method presented by Sherard, et al. End effects can now be evaluated

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