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STRONG-MOTION INSTRUMENTATION OF EARTH DAMS

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INTRODUCTION

Since the failure of an earth dam during a major earthquake may have catastrophic consequences, it is imperative that the safety of the dam be a primary consideration in its design. There are many questions that can be posed to the designers responsible for ensuring the earthquake resistance of an earth dam. For example, what is the expected ground motion in the region of the dam? For a defined ground motion, what is the anticipated response of the embankment? These questions and others must be addressed in order to establish the safety of an earth dam. The past performance of earth dams during seismic events provides valuable information for answering these questions. Unfortunately, the amount of recorded data of earth dam responses during major earthquakes is quite meager.

To obtain critical information regarding a dam's earthquake behavior, it is necessary to install seismic instrumentation in the region close to the dam and on the earth embankment. In particular, strong-motion instrumentation placed at the dam location will provide the most valuable information available for describing the seismic behavior of the structure. Various federal, state, and local agencies have initiated strong-motion instrumentation programs with the general goal of obtaining information about earth dam response during earthquakes. This report is intended to assist in the development and implementation of those programs.

In addition to recommendations for locating strong-motion instrumentation and other types of seismic instrumentation, this investigation concerns the establishment of guidelines for the selection of earth dams to be instrumented. It should be noted that the recommendations for strong-motion instrumentation are significantly influenced by the assumptions that have been made in this report. Despite this limitation, the implementation of the proposed recommendations should result in the acquisition of much-needed data on the seismic response of earth dams.

I. OBJECTIVES OF STRONG-MOTION INSTRUMENTATION PROGRAMS FOR EARTH DAMS

One general purpose of all strong-motion instrumentation programs for earth dams is to obtain information that will help define the seismic response of earth dams and advance our knowledge of earth dam behavior during earthquakes. However, the specific goals of the instrumenting agency will determine to a large extent the number, type, and location of the strong-motion instrumentation used in the program. These goals may be one of the following: to obtain data for use in the analysis and design of future earth dams; to obtain data for evaluating the earthquake hazard of existing earth dams; or to obtain data which will be used as a basis for determining the safety of earth dams subjected to strong ground motions.

For the purposes of this report it is assumed that one of the primary goals of the strong-motion instrumentation program is the acquistion of data for use in improving the design process of future earth dams or for evaluation of the seismic hazard of present earth dams. Consequently, the strong-motion instrumentation schemes presented in this report are designed to meet these goals.

Strong-motion instrumentation programs for buildings and bridges may have as their principal objective the determination of forces in the structure caused by the earthquake, or the identification of some mathematical model which describes the seismic behavior of the structure. It would be desirable if a strong-motion instrumentation program for earth dams had similar specific objectives. However, because of our lack of understanding of fundamental earth dam response during earthquakes, such lofty goals are somewhat premature. Nevertheless, the strong-motion instrumentation schemes presented herein should result in the acquisition of data which will advance the state-of-the-art in this field.

II. DYNAMIC CHARACTERISTICS OF EARTH DAMS

Various types of information contribute to our present understanding of the dynamic behavior of earth dams. Mathematical models have been developed over the years to describe the vibrational modes of response of dams and to assist in other areas pertaining to the seismic analysis of dams. Experimental results, especially those obtained from full-scale forced vibration tests, have provided insight into the characteristics of earth dam behavior. Records obtained from instrumented dams during strong-motion earthquakes are valuable sources of information regarding the seismic response of dams. This section discusses the dynamic characteristics of earth dams which have been determined by the various methods just mentioned. Emphasis is placed on describing the modal responses of earth dams, because this information in particular is utilized in the selection of strong-motion instrumentation locations. Discussion will be limited to those modes that are considered to be important in the earthquake response of earth dams.

It should be emphasized that although an earth dam can theoretically respond in an infinite number of vibrational modes, only a few of these modes are likely to substantially contribute to the overall response of the dam during a major earthquake. Generally speaking, only those modes which have natural frequencies below some specific value can be expected to be significantly excited by the earthquake-induced ground shaking. All of the modes which have frequencies above this value can be eliminated from consideration. However, not all of the remaining modes will significantly contribute to the total response of the dam, and it is not always possible to discern which of the remaining modes, if any, will predominate in the response. Hence, the selection of particular modes for consideration involves a certain amount of engineering judgment.

Characteristics Determined from Analytical Methods

The analytical determination of modal characteristics of an earth dam is not an easy problem. Uncertainties in the properties of the embankment materials, complex geometry of the dam, and other factors contribute to the difficulty of the task. Simplifying assumptions must be made at each step of the analysis to make the problem tractable. Therefore, it is not surprising that different analyses of particular earth dams show large variations in the calculated modal properties.

Despite the limitations of analytical procedures, several general observations can be made regarding the modal characteristics of earth dams. However, even these generalities must be predicated on several restrictive assumptions. These assumptions are required so that current analytical techniques can be used to obtain information regarding an earth dam's modal properties.

The following discussion is intended to illustrate the general modal characteristics of an earth dam through a case study. For this study it is assumed that the dam under consideration has a crest length that is relatively long in comparison to its maximum height above streambed level (length/height approximately greater than 4:1). The abutments are assumed to have steep slopes and the underlying foundation and bedrock levels can be modeled as horizontal planes without introducing significant errors. Upstream and downstream faces are considered to have uniform slopes that are relatively flat (slope approximately greater than 2:1). The underlying layer of foundation soil is considered to be relatively thin (or non-existent) compared to the maximum height of the dam. Abutments must also be considered rigid in comparison to the embankment material. The embankment material is assumed to be adequately represented by a constant set of elastic properties throughout the dam. An earth dam which generally meets these conditions will be referred to as an "ideal" earth dam (fig. 1).

It is useful to classify modes of vibration according to the direction of the predominant motion. That is, modes can be categorized as being transverse (upstream-downstream), longitudinal, and vertical. However, one three-dimensional analysis (Frazier, 1969) has shown that each mode contains components of motion in all three directions and that personal judgment is sometimes required to classify modes into one of the three categories. Furthermore, some modes have deformation patterns that are similar to the deflected shape of the dam if it was rocking about its longitudinal axis. These modes will be referred to as rocking modes.

Both two-dimensional (Clough and Chopra, 1966; Martin and Seed, 1966) and three-dimensional analyses (Frazier, 1969) have indicated that the lowest mode of vibration consists of predominant motion in the transverse direction with points on the vertical center-line axis of the dam displacing more than corresponding points on the faces. Fig. 2 shows the general shape of this mode for the "ideal" earth dam. This mode is also referred to as a shear mode because its deformation pattern is similar to that of a vertical shear beam. Note that the modal displacements are symmetric about a transversely-oriented vertical plane that intersects the longitudinal axis of the dam at its midpoint.

The next mode with predominant motion in the transverse direction is depicted in fig. 3. Displacement patterns at any vertical section perpendicular to the longitudinal axis of the dam are quite similar to those of the first transverse mode. However, for this mode the deformations are anti-symmetric about the transversely-oriented vertical plane through the dam's midpoint.

A higher mode that is symmetric about the transversely-oriented vertical plane at the midpoint of the dam but which has three extremums of transverse motion over the dam's length is shown in fig. 4. Once again the displacement pattern over the height is very much like that of the fundamental transverse mode.

Analyses also predict the existence of transverse shear modes which have points of zero transverse displacement on transversely-oriented vertical planes perpendicular to the longitudinal axis of the dam. Fig. 5 shows the approximate deformation shape for the lowest mode of this type.

Modes in which the predominant motion is in the longitudinal direction of the dam have also been determined by analytical methods. The lowest mode in this direction is depicted in fig. 6. An interesting aspect of this mode is that in addition to the longitudinal displacements there exists anti-symmetric vertical deformations. The rigidity of the abutments and the length of the dam have a significant influence upon the particular shape of this mode.

Fig. 7 shows the general deformation pattern for the lowest mode in which vertical motion predominates. As with many of the other modes, there is strong coupling between the displacements in the three directions for this mode. Although the largest deformations are in the vertical direction, significant components of symmetric longitudinal and transverse motion are present.

Rocking modes contain displacement components that are largely oriented in the transverse and vertical directions. Analyses have predicted that deformations on the faces of the dam would be substantial if the dam significantly responds in rocking behavior. The deformation shape of the lowest rocking mode is depicted in fig. 8.

For most earth dams there are many more modes that may noticeably contribute to the overall response of the dam. However, it is the author's judgment that consideration of the modes just described is sufficient for the purposes of this study.

Characteristics Determined from Experimental Methods

Results from various experimental procedures are often utilized in the seismic analysis of earth dams. Geophysical in-situ investigations and laboratory testing provide critical information regarding the properties of the embankment materials. Tests on scale models of earth dams can also enhance our understanding of the dynamic behavior of dams. Nonetheless, the following discussion regarding experimental methods is restricted to results obtained from full-scale vibration tests. These tests currently are the best experimental means for evaluating the dynamic characteristics of earth dams and, in particular, the dam's modal properties.

Keightley's work (Keightley, 1964) represents one of the first attempts to establish the vibrational characteristics of an actual earth dam by means of rotating vibration generators and associated instrumentation. Mode shapes, natural frequencies, and equivalent viscous damping constants were derived from the test results for the first four modes in the transverse direction. The measured mode shapes for the first three modes were quite similar to those shown in figs. 2, 3, and 4, respectively, while the fourth mode had a deformation pattern that was generally anti-symmetric along the crest with three points of zero modal displacement. One interesting observation by Keightley was that there appeared to be substantial differences between the modal amplitudes for locations on the downstream face and corresponding points on the upstream face. The data suggest that the upstream and downstream faces move differently from each other and that this difference is dependent upon the frequency of excitation.

Forced vibration tests were also performed on a relatively small earth dam in Northern California (Martin and Seed, 1966). Due to instrumentation limitations, only data pertaining to the fundamental transverse mode were considered suitable for analysis. The experimental set-up included sensors lowered into boreholes so that motions within the body of the dam could be measured. Results from the tests are in general agreement with those obtained by Keightley for the first transverse mode. However, responses measured in the borehole and at corresponding elevations on the face of the dam showed major differences in amplitude, suggesting the existence of tensile and compressive zones over horizontal planes.

An extensive experimental investigation of a large earth dam was performed at Santa Felicia Dam in Southern California (Abdel-Ghaffar and Scott, 1981(a) and 1981(b)). One of the principal findings of the forced vibration part of this investigation was that modal coupling exists between the three translational responses. The fundamental transverse mode contained significant longitudinal and vertical components. There were also indications of strong coupling between the transverse and longitudinal directions for some modes. Rocking behavior was also observed in these tests. Many modes in the transverse and longitudinal directions were identified by the test procedures but it was difficult to classify each particular mode according to the direction of predominant motion due to the strong coupling. Observation of the first few transverse mode shapes showed no major differences in the shape of these modes as compared to those obtained in earlier investigations.

Characteristics Determined from Analysis of Strong-Motion Records

The performance of earth dams during earthquakes provides additional insights into the modal characteristics of a dam's response. During the San Fernando Earthquake of 1971 and the Southern California Earthquake of 1976, Santa Felicia Dam apparently responded primarily in its fundamental transverse mode (Abdel-Ghaffar and Scott, 1979 and 1981(b)). Contributions from higher modes in the transverse direction were generally not significant. However, it should be noted that only symmetric transverse modes were likely to be observed in the recorded data due to the location of the single crest instrument near the midpoint of the dam.

The response of Santa Felicia Dam during the two earthquakes indicated that several modes contributed substantially to the overall response in the longitudinal direction. Analysis of vertical motions also suggests that many modes in this direction may have significantly participated in the response. Due to the fact that only one instrument was located on the earth embankment during the earthquakes, very little information regarding the possible rocking responses or other coupled modes could be obtained.

Analysis of strong-motion measurements obtained during the Oroville Earthquake of 1975 indicate that Oroville Dam oscillated primarily in its fundamental transverse mode for a substantial duration of the record (Vrymoed, 1981). However, instrumentation problems were encountered during the earthquake, and other modal characteristics are difficult to establish.

One particular earth dam (Long Valley Dam), which was heavily instrumented, yielded many strong-motion records during a series of earthquakes in 1980 (Turpen, 1980). Measurements from twenty-two accelerometers located at various positions on the dam and in the surrounding region were obtained. In-depth analysis of the records, however, has yet to be performed. Hence, the dynamic characteristics of the dam, including modal properties, have not yet been discerned from the strong-motion data.

III. CURRENT STRONG-MOTION INSTRUMENTATION OF EARTH DAMS

The main intent of this section is to summarize the strong-motion instrumentation that currently exists at earth dams. Discussion is also focused on the earth dam instrumentation programs instituted by various federal, state, and local agencies. In particular, information regarding the number and locations of strong-motion instrumentation employed at earth dam sites is presented. The following paragraphs describe the major strong-motion instrumentation programs that include instrumentation of earth dams as part of the program.

The U.S. Army Corps of Engineers (ACOE) operates a strong-motion instrumentation program that currently includes over 80 earth and rockfill dams in the United States. This number represents more than half of the total number of earth dams in this country which are instrumented with strong-motion accelerographs. Initially, the program was a cooperative effort with the United States Coast and Geodetic Survey to instrument dams in California. Expansion of the program took place following the San Fernando Earthquake of 1971, and presently earth dams in more than 25 states are instrumented by the Corps.

A major objective of the ACOE program is the measurement of earthquake motions so that earthquake-resistant design methods may be improved. As one means of achieving this goal, the Corps has established requirements for the selection of earth dams for instrumentation. In general, dams which are over 100 ft high and located in moderate or high seismic risk zones are chosen for instrumentation. Additional earth dams may be instrumented where unique embankment and/or foundation conditions exist.

The Corps has also established recommendations for the number, type, and locations of strong-motion instrumentation at the selected earth dams. Fig. 9 depicts this instrumentation scheme. Note that each instrument listed in this figure refers to a three-component strong-motion accelerograph.

The Office of Strong Motion Studies of the California Division of Mines and Geology operates the California Strong-Motion Instrumentation Program (CSMIP). This program, which was established in 1972, is designed to acquire records of the earthquake response of representative structures in addition to strong ground motion records. As part of this program more than 15 earth dams have been instrumented.

There are several objectives of the CSMIP and one of the primary goals is to obtain data which can be used to improve engineering design practice. Consequently, some of the earth dams in this program are extensively instrumented to provide detailed information regarding the seismic behavior of the embankment in addition to the free-field motions. Long Valley Dam, located near Bishop, and Puddingstone Dam in the Los Angeles area, are the most heavily instrumented dams in this category. A schematic view of the strong-motion instrumentation at Long Valley Dam is shown in fig. 10. The extent and locations of the instrumentation at other earth dams in this program widely vary.

Several earth dams in California are instrumented under a program supported by the California Division of Water Resources (CDWR). The intent of this program, which includes ten earth dam sites, is to obtain data at facilities in the California State Water Project. The number of three-component accelerographs at the dams in this program ranges from one to six.

The U.S. Bureau of Reclamation has instrumented earth dams in six Western states. This program, which was initiated in the 1940's, has resulted in the instrumentation of approximately 15 earth dams. Typically, two or three accelerographs are located at dam sites in this program. However, the extent of instrumentation at these dams ranges from a single three-component accelerograph located on one dam abutment to more than 15 accelerometers placed on one particular dam (Casitas).

Six earth dams have been instrumented with strong-motion accelerographs by the Metropolitan Water District of Southern California. At the majority of these dams a single instrument was placed on the abutment of the dam and no more than three instruments exist at any dam site in this program.

Monticello Dam in South Carolina is the only earth dam in this country which is solely instrumented by the U.S. Geological Survey. However, most of the previously mentioned agencies have co-operated with the USGS regarding the planning, installation and maintenance of the instrumentation used in these programs. The processing and archiving of strong-motion records obtained at earth dams under many of these programs is the responsibility of the USGS. Additional information regarding the extent and locations of strong-motion instrumentation at earth dams has been published by the USGS (Switzer, Johnson, Maley and Matthiesen, 1981).

In summary, the extent of strong-motion instrumentation that currently exists at earth dams varies greatly. In the majority of the cases that were investigated, no more than three strong-motion accelerographs exist to provide information pertaining to the free-field motion and the response of the embankment. However, the number of accelerographs employed to measure the structural and free-field responses at any particular earth dam is strongly influenced by the goals of the instrumenting agency and other factors.

IV. GENERAL GUIDELINES FOR SELECTION OF EARTH DAMS TO BE INSTRUMENTED

There are many considerations that should go into the selection of an earth dam to record strong-motion earthquake responses. Obviously, the general purpose of the instrumentation program should be taken into account when the choice of a particular dam to be instrumented is made. However, more specific aspects of the selection process also need to be considered. The following discussion concerns the criteria that should be utilized in selecting an earth dam for strong-motion instrumentation. In particular, criteria regarding dam location and dam type are presented.

It should be re-emphasized that one of the goals of the instrumentation program is assumed to be the recording of data that will be used primarily for improving engineering analysis and design practices, as opposed to monitoring purposes. This implies that the dams selected for instrumentation not only should be expected to yield strong motion data during some time period but, additionally, the information obtained should be the most appropriate for use in achieving the desired goals.

Criteria pertaining to the selection of the dam location is assumed to be similar to the criteria developed for buildings and highway bridges (Rojahn, 1976, and Rojahn and Raggett, 1981). The fundamental assumption utilized in these criteria is that strong-motion data regarding structural behavior during damaging-level earthquakes are the most desirable types of information. Factors that enter into this criteria include frequency of seismic activity and proximity to earthquake source region and surface rupture zones.

The type of dam selected for instrumentation is critically important if the goals of the program are to be achieved. It would be very desirable if the chosen dams were typical of many earth dams so that information obtained from the selected ones could be easily extrapolated for use on other dams.

However, because of the unique nature of dam sites and other factors, earth dams are usually quite dissimilar in several major aspects. Unfortunately, the "ideal" earth dam described in Chapt. II is not typical. Despite the wide variability of important features among earth dams, criteria regarding dam type, which are consonant with the goals of the instrumentation program, can be established.

In general, it is preferable that the dams selected for strong-motion instrumentation have features that are in reasonable agreement with those described for the "ideal" dam. It is recognized that very few dams, if any, will meet all of these requirements. However, because of our lack of fundamental understanding of the seismic behavior of earth dams, it is necessary to specify that the instrumented dams be as simple and easy to analyze as possible. If the majority of these requirements are not met reasonably well, then the task of interpretting the strong-motion data and formulating accurate mathematical models of the dam's behavior will become much more difficult.

V. GUIDELINES FOR DAM SITE INSTRUMENTATION LOCATIONS

For the purposes of this report, strong-motion instrumention networks at dam sites are subdivided into five categories:

1) Free-field motion instrumentation
2) Input motion instrumentation
3) Response motion instrumentation
4) Failure motion instrumentation
5) Additional seismic instrumentation

Free-field motion refers to the ground motion in the immediate vicinity of the dam site that is not influenced by the presence of the dam. Input motions are the motions of the adjacent abutments and underlying foundation material of the embankment. The small-deformation movements of the earth embankment which forms the dam constitute the response motions. Failure motions pertain to the large deformations which may occur prior to, or during, partial or total failure of the embankment.

It is assumed that all instrumentation which is intended to record ground and structure motions will consist of strong-motion accelerographs. The instrumentation in Category 5 will include dynamic pore-pressure transducers and other equipment whose purpose is to better describe the seismic behavior of the dam.

In an instrumentation scheme at a dam site there are at least five major factors to be considered: 1) Foundation conditions, 2) Local topography, 3) Geometry of dam, 4) Embankment materials, and 5) Expected nature of the motions. The proposed instrumentation scheme for each of the five categories listed previously should take into account all of these factors. Additional considerations, such as the method of construction, may be required for some of the categories.

Schemes designed to record motions for each of the first four categories are discussed in the following sections. Instrumentation that is intended to record data other than acceleration responses during major seismic events is also discussed. Specific recommendations are presented for instrumenting an "ideal" earth dam and the surrounding region.

A. Free-Field Motions

Instrumentation that is designed to measure free-field motions near a dam must be located at a distance from the structure such that any recorded motion would be essentially the same as that obtained if the dam were not present. It is highly desirable to place this instrumentation at sites in which the foundation conditions are similar to those of the dam, and hence locations near the dam are preferable. However, because of the very large mass and dimensions of the dam it may be necessary to place this instrumentation relatively distant from the dam to avoid any influence from foundation-structure interaction. Unfortunately, there is little experimental data to help in estimating the required distances between the free-field sites and the dam itself.

If the foundation conditions vary over the region of the dam, (e.g., rock abutments with an underlying soil layer of alluvium) then several free-field sites would be desirable so that free-field and input motions that were recorded on the same material type could be compared.

If a free-field instrumentation site is chosen for buildings and bridges, it is typically located at a distance from the center of the structure approximately one to one-and-a-half times the shear wavelength in which the wave period is equal to the fundamental period of the structure (Rojahn and Raggett, 1981). This distance will be in the range of approximately 200 ft to

1000 ft for most bridges and small structures and, hence, the location of the free-field instrumentation site is relatively distant from the structure compared to the structure's plan dimensions. Experimental and analytical data confirm that the use of the above criterion in selecting free-field sites will minimize the influence of the structure upon the free-field motion. However, free-field siting requirements for dam structures may not conform to this criterion.

For one typical large earth dam the fundamental period of vibration in the transverse direction has been estimated from full-scale forced vibration tests to be approximately 0.61 sec (Abdel-Ghaffar and Scott, 1981(a)). Using this value and an assumed surface shear wave velocity of 1000 ft/sec, the required distance(s) from the center of the dam to the free-field site(s) would be between 610 ft and 915 ft based on the above criterion. However, the base width of many earth dams is on the order of 1000 ft or more and, hence, the calculated location of the free-field site might be within the dam itself. Therefore, it appears that the criterion used for siting free-field instrumentation for buildings and bridges is not applicable to earth dams.

Additional analytical studies (Chen, Lysmer, and Seed, 1981) have suggested that the influence of a structure upon the free-field motion caused by horizontally-propagating waves in a soil layer is only significant in the region very near the structure. These findings imply that instruments intended to record free-field motions can be located relatively close to the structure of interest.

Free-Field Motion Instrumentation

Due to topographic considerations and the immense size of earth dams, it is obvious that one free-field site is inadequate in describing the free-field motion. The recommendations for free-field instrumentation locations near an "ideal" earth dam are as follows:

1) In the region of both abutments.

2) Downstream of the dam.

Three-component accelerographs are suggested for each free-field site with the orientation of the components corresponding to the transverse, longitudinal, and vertical axes, respectively, of the dam (fig. 11).

The abutment sites should not be adjacent to the dam but rather at a distance away from the ends of the dam approximately equal to the shear wavespeed times the fundamental period of vibration. Based on the discussion presented previously in this section, it is anticipated that the influence of the dam's presence upon the recordings at these locations will be insignificant.

At the downstream site the instrumentation should be placed on the same foundation material that underlies the dam. The distance between the downstream toe and the location site should be approximately the same as that specified earlier for the instruments in the region of the abutments. This distance is in reasonable agreement with the criteria used by the Corps of Engineers (WES, 1974).

For many cases the foundation material directly beneath the embankment will not be bedrock. In these situations an additional free-field site should be located on the bedrock surface in the downstream region. The criteria used to establish the distance from the downstream toe to the instrument location is the same as that specified previously. It is preferable that the bedrock site be located beneath the ground surface, but a surface location may be used if local topographic effects are not expected to be significant at the chosen site.

This proposed scheme for measuring free-field motions should provide information regarding phase lags and direction of the incoming seismic waves. It may also permit an evaluation of the influence of the local topography on the ground motion since the downstream and abutment instruments will have an elevation difference of at least several hundred feet. However, this topographic effect may be insignificant or difficult to deduce from the recorded data. The alteration of the free-field rock motion by the foundation layer may also be determined if instruments are located at the ground level and at a bedrock location beneath the surface.

B. Input Motions

The nature of input motions to a dam is significantly more complex than that of most buildings or bridge structures. For the latter cases the input motions to the structure being considered are usually assumed to act at discrete locations (concrete mat foundation, column footing, etc.) and instrumentation schemes can be designed to adequately measure these motions. Furthermore, because these foundations are relatively rigid and oftentimes have small plan dimensions, the assumption of uniform motion for all points on the foundation can usually be justified. However, for earth dams the input motion to the dam occurs over a very large and continuous region encompassing the underlying foundation material and the abutments. The design of an instrumentation scheme to record these motions is indeed quite a challenge.

The foundation conditions of an earth dam must be considered in the assessment of the input motions to the dam. The principal factors in this assessment are the mechanical properties of the foundation material. If the dam is founded directly on bedrock, then the input motions might be considerably different from the case in which some existing soil layer(s) serve as the underlying foundation material.

In the construction of earth dams all soil layers may not be removed prior to the placement of the embankment material. For example, the embankment of the Lower San Fernando Dam rests on an alluvium deposit. This foundation material is relatively weak compared to the underlying shales and sandstones. In other cases (e.g., Santa Felicia Dam, Warm Springs Dam), portions of the embankment extend down to bedrock. Additionally, the foundation soil may vary in thickness, thus influencing the input motions to the dam.

Soil-structure interaction is a phenomenom that should be addressed in any discussion of input motions. As mentioned previously, the input motions to the dam may be noticeably different from the free-field motions. The presence of the dam will alter the free-field motion due to the stress field created by the dam's motion upon its foundation.

Numerous researchers have investigated the effects of soil-structure interaction upon building response. However, surprisingly little attention has been focused on soil-structure interaction of earth dam-foundation systems. Many researchers circumvent the problem by assuming that the foundation material is essentially rigid in comparison to the embankment. For many cases this assumption is justifiable but if the dam is situated on a relatively soft soil layer then soil-structure interaction may be a major factor in the overall response of the dam. Idriss, Mathur, and Seed (1974) have indicated that these interaction effects are significant for cases in which a wide dam rests on a relatively thin foundation layer.

Local topography may have a significant influence upon ground motions near an earth dam. The fact that many earth dams are located in narrow valleys in which reflections of the seismic waves may take place complicates the nature of the input motions. Furthermore, earth dams may consist of several embankments located between rock outcroppings (e.g., Monticello Dam, South Carolina). For these situations analysis of the incoming seismic motions is extremely difficult.

Analytical investigations (Reimer, Clough, and Raphael, 1974) have suggested that the nature of the local topography was a major factor in the unusual recording obtained at the abutment of Pacoima Dam during the San Fernando Earthquake in 1971. Field studies in the region near Pacoima Dam (Davis and West, 1973) have indicated that during the San Fernando event considerable amplification of the underlying rock motions may have occured in the flanks of the mountain that forms one of the dam abutments.

Geometry of the earth embankment and local topography are interrelated topics. Because of the local topography earth dams are usually several times longer at the crest level than at the base. Additionally, the abutments seldom have a uniform slope. Both longitudinal and transverse sections through the dam may differ appreciably along the width and length, respectively, of the dam. This three-dimensional nature of the dam's geometry must be considered in the design of the instrumentation.

Because of the spatial dimensions involved with many earth dams, differential ground motions may be a serious consideration. In situations in which the foundation material is not bedrock, differential ground motions caused by travelling waves could be a very major factor in the overall response of the dam. Even for cases in which the underlying foundation material and abutments are composed of competent bedrock, significant differential motions may exist between the underlying rock and the abutments simply due to the large distances involved.

Dibaj and Penzien (1969), and Chopra, Dibaj, Clough, Penzien, and Seed (1969) concluded that if the spatial variation of the foundation motion is omitted in the analysis, unconservative errors in estimating the response of the dam are likely to occur. These analyses only considered the variation of ground motion along an axis through the width of the dam. In the longitudinal direction of the dam the spatial variation of motion may be more pronounced due to the larger distance involved. Bycroft (1980) and others have stressed the importance of differential ground motions in the seismic response of large structures such as dams.

Rojahn and Raggett (1981) have presented guidelines for estimating the maximum spacing between instruments that are intended to measure input motions to highway bridges. Their recommendations are based on the recognition that differential ground motions must be considered if mathematical modelling studies and force determinations are to be sufficiently accurate. They recommend that the maximum spacing between input measuring instruments be estimated from the natural period of the assumed dominant mode of response and the propagation velocity of the dominant wave forms. If typical values of these quantities for earth dams are used, then, based on the guidelines for highway bridges, the recommended maximum spacing between instruments would be approximately 100 ft in both the longitudinal and transverse directions of the dam. When one considers the very large dimensions of earth dams, it becomes readily apparent that the spacing criterion for bridge input instrumentation is totally unrealistic when applied to earth dams.

Input Motion Instrumentation

Despite the inadequacies inherent in any instrumentation scheme for measuring input motions, judicious selection of the instrumentation locations should provide critical information that will enhance our basic understanding of the seismic behavior of earth dams. The proposed instrumentation locations for measuring the input motions to an "ideal" earth dam are as follows:

1) On both abutments adjacent to the dam at, or slightly below, the crest level.

2) A few feet beyond the base of the downstream toe on a cross-section through the maximum height of the embankment.

3) Directly beneath the dam crest within the upper few feet of the foundation soil on the same cross-section as that in 2.

4) Directly beneath the dam crest within the upper few feet of the underlying rock on the same cross-section as that in 2 (assuming that the embankment does not extend to the bedrock level at this section).

It is recommended that three-component accelerographs be placed at each of these locations and that the axes of the instruments correspond to the longitudinal, transverse, and vertical axes of the dam (fig. 12).

By locating instruments on both abutments at the crest level it would be possible to evaluate the phase lags of the input motions at this elevation. This information would be helpful in estimating the rocking and anti-symmetric responses of the dam as well as the in-phase translational motions. Abutment recordings would also provide valuable data regarding abutment-dam interaction effects.

It is interesting to note that in many seismic analyses of earth dams the input motions to the model of the dam are intended to be representative of the underlying bedrock motions, yet these input motions are usually determined from recordings obtained from instruments located on the dam abutments. The proposed instrumentation scheme would test the validity of this practice.

One purpose of the instruments located near the downstream toe and at the foundation level beneath the center of the dam is to provide data concerning differential ground motions along the maximum transverse section of the dam. This section is most often used in analyzing the dam's response. Recordings from the foundation-level instruments will also provide information concerning the influence of the dam's overburden upon the input motions at the streambed level.

The two instruments that are located at the foundation and bedrock levels beneath the crest should provide valuable data which will assist in determining the interaction of the dam and its foundation. For situations in which a central core extends below the main foundation level down to the bedrock level, the instrument at the foundation level would not be located directly beneath the crest. It should be placed a few feet from the interface of the core and shell materials, but located within the upper few feet of the foundation material that underlies most of the dam.

It should be emphasized that the proposed instrumentation scheme for measuring input motions will only provide information regarding spatial variations of motion and influences of foundation conditions at one transverse and one longitudinal section of the dam. The complete three-dimensional characteristics of the input motions to the dam will not be totally recorded by the proposed scheme but the instrumentation should provide a good definition of the input motions to the structure.

C. Response Motions

It is desirable to locate instruments which measure response motions such that they record all significant motions of the dam. The choices for specific locations of the instruments will be primarily dependent upon the expected behavior of the dam during a seismic event. Various analytical and experimental methods can be used to help determine these locations.

One approach that can be adopted for selecting instrument locations on a structure is to position the instruments such that they record the maximum responses of the natural modes that are deemed important in defining the structure's overall behavior. Rojahn and Matthiesen (1977), and Rojahn and Raggett (1981) have utilized this method in recommending instrumentation locations for buildings and highway bridges, respectively. However, this approach is based on the assumption of linear structural behavior and is only strictly valid for a relatively small range of structural deformations.

Despite the fact that earth dams exhibit nonlinear response during seismic events, even at low levels of excitation, the assumption of linear behavior will be presumed adequate for the purposes of this study. Consequently, the selection of the instrument locations can be based on the procedures proposed by Rojahn and Matthiesen (1977), and Rojahn and Raggett (1981). It is assumed that these guidelines, which were originally developed for buildings and highway bridges, respectively, are also applicable to earth dams.

The procedure for selecting instrument locations first requires that all possible mode shapes of the structure be identified. Modes that are not expected to be significantly excited by the seismic waves or substantially participate in the overall response of the structure are then eliminated from consideration. Finally, the remaining modes are used to identify the locations of the instruments.

Response Motion Instrumentation

The instrumentation proposed in this section is intended to provide information that will identify the fundamental mode of predominant response in the directions corresponding to the transverse, longitudinal, and vertical axes of the dam. Additional modes that are expected to significantly contribute to the overall response of the dam will also be identified by the proposed scheme. If information regarding higher modes is desired then a considerably more extensive instrumentation scheme is necessary.

It should be noted that instrumentation that is designed to merely identify particular modes of response may result in the omission of important information which would help in describing the seismic behavior of an earth dam. For example, the fundamental transverse mode can be identified by a relatively simple instrumentation scheme. However, there are substantial differences between the shape of this mode as predicted by theoretical models and that observed in full-scale forced vibration tests (Keightley, 1966, and Martin and Seed, 1966). Hence, it would be very desirable to design an instrumentation scheme that not only would identify this particular mode but also provide information regarding the actual mode shape. The proposed instrumentation scheme for measuring response motions addresses this particular issue.

Based on the discussion previously presented in this section, the recommendations for locations of instruments which are intended to measure the response motions of an "ideal" earth dam are as follows:

1) On the crest on a cross-section through the maximum height of the dam and preferably at the mid-point along the crest.

2) On the crest at a distance from either abutment equal to approximately one-fourth to one-third of the crest length of the dam.

3) On the downstream slope at approximately four-tenths of the maximum dam height on the same cross-section as that in 1.

4) On the upstream slope at approximately four-tenths of the maximum dam height on the same cross-section as that in 1. (Note that this location will be below the water level in the resevoir most of the time.)

5) On the downstream slope on the same cross-section as that in 2) and on the same horizontal plane as that in 3. (Recall that the dam under consideration is assumed to be relatively long and also to have steep abutments such that location 5 is indeed on the dam itself and not on the abutment.)

6) Directly beneath the crest at approximately four-tenths of the maximum dam height on the same cross-section as that in 1.

7) Directly beneath the crest at approximately seven-tenths of the maximum dam height on the same cross-section as that in 1.

The number and orientation of accelerometers at each of these locations will be discussed in terms of the expected predominant modes of response. Location numbers refer to the specific positions on the dam just described (fig. 13).

Accelerometers oriented in the transverse direction should be placed at locations 1, 3, 4, 6, and 7 to provide information regarding the fundamental mode of response in the transverse direction. Note that all of these accelerometers are on the vertical plane through the maximum height of the dam and this plane is expected to experience the largest deformations in the transverse direction. Comparisons of the responses at the crest and at the four- and seven-tenths height locations may help in determining the nature of the mode shape along a vertical axis through the center of the dam and over the height of the dam along the upstream and downstream slopes. Data which will be obtained from these accelerometers will help to establish if the dam is deforming primarily in a shearing mode or if other types of deformation are significant.

Analysis of the three transverse motions at the four-tenths height locations may establish the existence of significant compressional or tensile zones over a horizontal plane. This information would be quite valuable in assessing the liquefaction potential of the embankment material. Additional information concerning the effect of hydrodynamic forces on transverse motions may be discerned from the response of the accelerometer at location 4. It also should be recalled that three additional transversely-oriented accelerometers are recommended at the foundation and bedrock levels on the same vertical plane that contains the response-measuring instruments, and comparisons of the input motions to the responses on this plane may result in important information regarding the behavior of the dam in its fundamental transverse mode.

To provide data for identifying the first mode in the longitudinal direction of the dam accelerometers oriented in this direction should be positioned at locations 1, 2 and 3. A vertically-oriented accelerometer at location 2 should also help in supplying information about this mode since analytical and experimental evidence indicate that this longitudinal mode is significantly coupled with anti-symmetric vertical motion along the crest. This vertical motion should be a maximum near location 2. The longitudinally-oriented accelerometer at location 3 will help to describe this mode shape over the height of the dam and also help distinguish the fundamental mode in this direction from higher modes.

The fundamental vertical mode will be recorded by vertically-oriented accelerometers at locations 1, 2, 3 and 6. Not only will the accelerometers at locations 1 and 6 be used to help identify this particular mode but their measurements can be compared to each other to evaluate the compressional and tensile strains in the vertical direction. Vertically-oriented accelerometers at locations 2 and 3 should supply data regarding this mode shape along the dam's length and over its height.

If the second transverse mode (anti-symmetric along the longitudinal axis) is excited by an earthquake, accelerometers oriented in the transverse direction at locations 2 and 5 should be used to provide data for identifying it. Data from these accelerometers, in addition to the transversely-oriented ones at locations 1 and 3, can be used to distinguish the first two transverse modes from each other. The accelerometers at the four-tenths height not only are employed to record motions which will help establish the characteristics of the mode shape over the height of the dam, but also to possibly provide information for identifying any higher transverse modes that have a point of zero displacement at some position over the dam's height. For these higher modes the maximum transverse response should not occur at the crest level but rather approximately at the level of the accelerometers located at the four-tenths height.

Rocking behavior about a longitudinal axis through the dam would be recorded by the vertically-oriented accelerometer at location 3 and the majority of the transversely-oriented accelerometers. The rocking mode contains large transverse components at locations 1 and 6 and data from the accelerometers at these locations would be helpful in identifying this mode. Because of the coupled nature of this mode, the phase relationships of the recorded motions may provide additional information regarding the existence of rocking response.

In summary, a total of fourteen accelerometers placed at seven separate locations on and within the dam are recommended for measuring the response motions of the dam. If it is assumed that the behavior of the dam can be represented in terms of its modal responses without introducing significant errors, then the modes that are identified by data from this instrumentation scheme should provide sufficient information to adequately describe the seismic response of the dam. However, in the event of a large earthquake in which damaging levels of motion may exist, additional instrumentation would be desirable to provide information regarding non-linear behavior and possible failure mechanisms.

In this instrumentation scheme the number of proposed accelerometers is larger than the number of accelerometers theoretically required to uniquely identify the modes previously described. However, because of the very close spacing of many modes and uncertainties regarding the actual shape of the modes, it may be very difficult to identify all of the predominant modes from a small number of response records. By employing a larger number of accelerometers and comparing the recorded responses, the modal characteristics can be established with a much greater degree of accuracy.

D. Failure Motions

The non-linear behavior of dam structures caused by strong ground motion is an area that is not well understood at the present time. Additionally, failure mechanisms in earth dams due to earthquakes are extremely complex. This lack of understanding complicates the task of recommending instrumentation which is intended to record failure motions of a particular dam in the event that partial or total failure of the embankment occurs. Some insight to the expected behavior of earth dams at high levels of ground motion may be gained by noting the damage sustained by various dams during seismic events. The following discussion concerns the damage that has been observed at earth dams following seismic occurences. Failure mechanisms are also discussed for those cases in which sufficient analysis has been performed to establish the mode of failure of the dam.

Damage sustained by earth dams during strong earthquakes can usually be classified into one of the following categories:

1) Longitudinal cracks, particularly in the region of the crest.

2) Transverse cracks which occur most often near the abutments.

3) Slides of portions of the upstream and downstream slopes.

4) Large scale deformations resulting in extensive slumping, spreading, and possible total failure of the dam.

Longitudinal cracks are the most common type of damage that takes place during strong ground shaking. These cracks typically range from a fraction of an inch to several inches wide and may extend to significant depths below the surface of the dam. Longitudinal cracking has been observed over various portions of the upstream and downstream slopes but it has most often occured near the crest. Cracking of this type was present at San Andreas Dam (1906), Dry Canyon Dam (1952), and at other locations (Seed, Makdisi and De Alba, 1977). The cause of this type of cracking is generally believed to be the transverse motions of the embankment and resulting differential settlements of various portions of the dam.

Transverse cracks are usually attributed to longitudinal motions and the settlements that result from these motions (Abdel-Ghaffar, 1980). This type of damage occurs less frequently than does longitudinal cracking, and it often develops in the region of the abutment-embankment interface. Due to the differences in the nature of the shaking between the abutment and the embankment, large tensile stresses may arise in this area and result in transverse cracks. Piedmont Dam (1906) and Santa Felicia Dam (1971) demonstrated this type of cracking behavior.

Damage of a more serious type occurs when a mass of soil slides from the upstream or downstream slope. Probably the most well-known example of this type of response occured on the upstream slope of Lower San Fernando Dam in 1971 (Seed, Lee, Idriss and Makdisi, 1975). However, many other instances of sliding are well documented (e.g., Yuba Dam (1951), Baihe Dam, China (1976)). Lateral vibrations that give rise to large shear stresses over some critical sliding surface are generally thought to be the cause of this behavior.

Total failure of a dam may occur due to large displacements of the embankment. Major settlement of the crest is often accompanied by spreading of the fill. Collapses of dams have been attributed to failure of the foundation material (Hosorogi Embankment, Japan, (1948)) and liquefaction of the embankment material (El Cobre Dam, Chile, (1965)). In many cases, however, the exact mechanism of failure cannot be determined.

Two cases in which the mechanism of failure has been extensively studied are the Sheffield Dam failure of 1925 and the slides that occured in Lower San Fernando Dam in 1971. For both of these examples dynamic analyses have been performed and laboratory tests of the embankment materials have been conducted.

The Santa Barbara Earthquake of 1925 resulted in the failure of Sheffield Dam located near the city. Examination of the dam after the event revealed that vertical fissures opened from the base to the top of the dam and that the rushing water carried the dam downstream in sections (Ambraseys, 1960). It has been suggested that failure was caused by sliding along a surface near the base of the embankment (Seed, Lee, and Idriss, 1969). This sliding was related to progressive liquefaction along the base in which material near the center of the dam initially liquefied and then additional regions in the upstream and downstream directions liquefied as the ground shaking continued.

During the San Fernando Earthquake of 1971 a massive slide occured in the upstream slope of the Lower San Fernando Dam. Seed, Lee, Idriss, and Makdisi (1975) investigated the mechanism of failure for this case. The reconstruction of the event indicated that high pore pressures initially developed in a zone of fill near the base of the embankment and upstream of the central core of the dam. A state of liquefaction ensued in this region and adjacent zones within the fill soon thereafter liquefied. Failure resulted when the shear resistance of the soil material was exceeded along a sliding surface. No evidence of failure was observed within the foundation soil.

In this discussion on failure motions of earth dams it must be recognized that many factors other than the nature of the ground shaking usually contribute to the partial or total failure of a particular dam. Foundation conditions, method of construction, relative density of the fill materials, texture of the fill, and other considerations are often key factors in the seismic stability of earth dams.

It is often very difficult, if not impossible, to pinpoint the exact cause of cracking or more serious damage. Since earth dams by nature have unique features of geometry, embankment materials, and construction methods, extrapolation of the knowledge gained from previous dam failures to existing dams should be undertaken with extreme care. Furthermore, most of the examples cited in this section pertain to dams constructed at least forty years ago. Due to advancements in design and construction, earth dams built since that time may not demonstrate similar types of failure modes should high-amplitude, long-duration ground shaking occur.

Failure Motion Instrumentation

The locations of instrumentation which will measure motions related to the partial or total failure of the dam under consideration are dependent upon the anticipated mode of failure. Based on the discussion presented in this section, these locations for the "ideal" earth dam are as follows:

1) Directly beneath the center of the dam within the embankment material but positioned a few feet above the foundation level on a cross-section through the maximum height of the dam.

2) On the upstream slope slightly below the crest level on the same cross-section as that in 1.

3) On the dam surface in the crest region near one of the abutments.

A three-component accelerograph should be located at 1 to record motions that might relate to failure of the embankment material near the base of the dam. If a clay core exists in the central region of the dam, the accelerometers should be positioned upstream of the core within the more granular fill material. Data obtained from these accelerometers may be quite valuable if a state of liquefaction initiates in this area.

Both transverse and vertical accelerometers are recommended at location 2 to provide information regarding longitudinal cracking of the dam if it should occur. Since longitudinal cracking is often accompanied by substantial settlement, two accelerometers are required to adequately describe this behavior. For dams in which fill is placed on either side of a central core the accelerometers should be positioned on the fill material.

A longitudinally-oriented accelerometer at location 3 may result in the acquisition of data regarding transverse cracks that occur near the abutments.

In summary, six accelerometers positioned at three locations on and within the dam are recommended for providing information pertaining to failure motions of an "ideal" earth dam. The layout for this aspect of the instrumentation scheme is depicted in fig. 14.

The proposed instrumentation scheme to record failure-related motions is primarily based upon observations of damage to earth dams from seismic events. Data obtained from these instruments may not be sufficient to determine the exact mechanism of failure because of the complexity of earth dam behavior due to high-intensity ground shaking. However, this instrumentation should provide the best available information regarding failure motions of dams in which the most common types of damage occur.

E. Additional Seismic Instrumentation

Strong-motion accelerographs probably provide the most important data for the person involved in analyzing the seismic response of earth dams. However, other types of information would also be valuable in establishing the behavior of dams during large earthquakes. Instrumentation which will provide data other than strong-motion records is discussed in this section. Recommendations for employment of the instrumentation are also set forth.

Instruments such as peak recording devices and seismoscopes have been placed on earth dams to supplement accelerograph records (WES, 1974). However, the use of these types of instruments is discouraged since strong-motion accelerographs can be installed which should result in the acquisition of much more valuable data than that provided by peak accelerographs or seismoscopes.

Instrumentation which measures responses related to the mechanical behavior of the embankment materials would greatly complement strong-motion accelerographs. In particular, instrumentation which would provide data concerning the deformation characteristics of the earth fill as the dam vibrates is desirable. Unfortunately, the state-of-the-art in seismic instrumentation is not sufficiently advanced to permit a completely reliable means for measuring the dynamic stress-strain behavior of in-place embankment materials.

One type of instrumentation which may be used to record information pertaining to material response is a dynamic pore pressure cell. Changes in pore water pressure that occur within the embankment material during strong shaking would be recorded by such a device. The data obtained from this instrumentation may be quite valuable in describing the overall behavior of the embankment, especially for circumstances in which a high liquefaction potential exists. For post-earthquake liquefaction studies, information provided by dynamic pore pressure cells is essential.

Dynamic strain gauges and soil stress cells would also be valuable tools in describing the seismic behavior of an earth dam. However, the past performance of dynamic equipment of this type in earth dams during earthquakes has not been totally satisfactory (DWR, 1979). At the present time it appears that additional development and testing of such equipment is necessary prior to its widespread deployment in earth dams. However, since it has been assumed that one goal of the instrumentation program is to advance the state-of-the-art, the use of this type of instrumentation may be warranted in some cases.

It should be noted that other instrumentation intended to record static responses of the dam is assumed to be present at the dam under consideration. Data obtained from traditional piezometers and other standard instrumentation can be used to help establish some characteristics of the dam's behavior prior to, and subsequent to, a seismic event. Comparisons of the static and dynamic responses may provide additional insight to the earthquake response of the dam.

It is recommended that dynamic pore pressure transducers be located at the following positions within the "ideal" earth dam:

1) Directly beneath the center of the dam within the embankment material but positioned a few feet above the foundation level on a cross-section through the maximum height of the dam.

2) Directly beneath the center of the dam at approximately four-tenths of the maximum dam height on the same cross-section as that in 1.

3) A few feet above the foundation level approximately midway between location 1 and the upstream toe and on the same cross-section as that in 1. This pore pressure transducer should be positioned within the granular material upstream of a clay core if one exists.

Figure 15 depicts the locations for this instrumentation.

By locating the instruments at the maximum section of the dam the most useful information regarding liquefaction potential should be obtained since this section is expected to undergo the largest deformations. Comparisons of the data recorded by the instruments near the foundation level may provide information regarding possible sliding surfaces. Analysis of the measurements from the four-tenths height and foundation level instruments may give an indication of the influence of overburden on pore pressure response. Comparisons between the dynamic pore pressure readings and accelerations at locations 1 and 2 may give additional insight to the dam's response. It should be stressed that the accelerometers and pore pressure devices should be separated by several feet so that the presence of one instrument does not affect the measurements obtained by the other.

Recommendations for locations of dynamic strain and stress instrumentation are not presented. When the reliability of such instrumentation is improved so that satisfactory performance in the field can be expected, consideration should be given towards recommending instrumentation types and locations.

VI. SUMMARY AND CONCLUSIONS

In addition to the development of guidelines for the strong-motion instrumentation of earth dams, this report has discussed criteria for selecting earth dams to be instrumented, objectives of strong-motion instrumentation programs for earth dams, an overview of existing strong-motion instrumentation at earth dam sites, and a discussion on the dynamic characteristics of earth dams.

It is recognized that the cost of implementing all of the proposed recommendations for instrumentation at a dam site would be substantial. Financial aspects have not been considered in the design of the instrumentation scheme because of the various goals and resources of the instrumenting agencies. However, it is essential that priorities be established to determine which instruments should be utilized to provide the most valuable data if only a few instruments can be employed.

Additional measures can be taken by earth dam designers that will assist in achieving the goals of the instrumentation program. For new dams which are being planned, consideration should be given to the inclusion of vaults located within the embankment at the positions suggested in this report. This would greatly facilitate the implementation of the strong-motion instrumentation since no boreholes would be required for the installation of the instrumentation after construction of the embankment.

It should be re-emphasized that a major limitation for advancing the state-of-the-art in the area of seismic behavior of earth dams is the paucity of recorded data of earth dam responses during major earthquakes. It is hoped that the implementation of the proposed guidelines for strong-motion instrumentation will help in alleviating this problem.

ACKNOWLEDGMENTS

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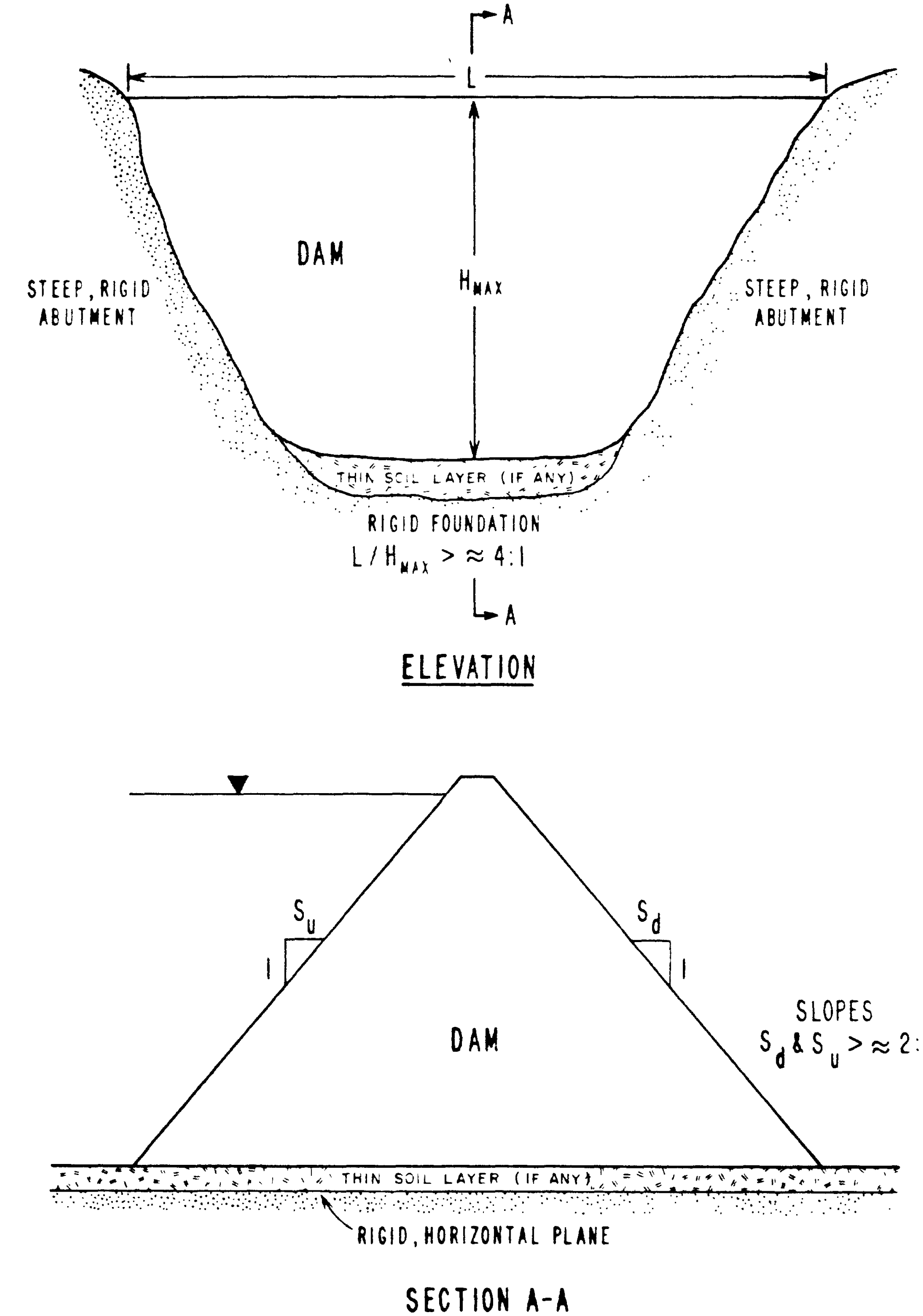
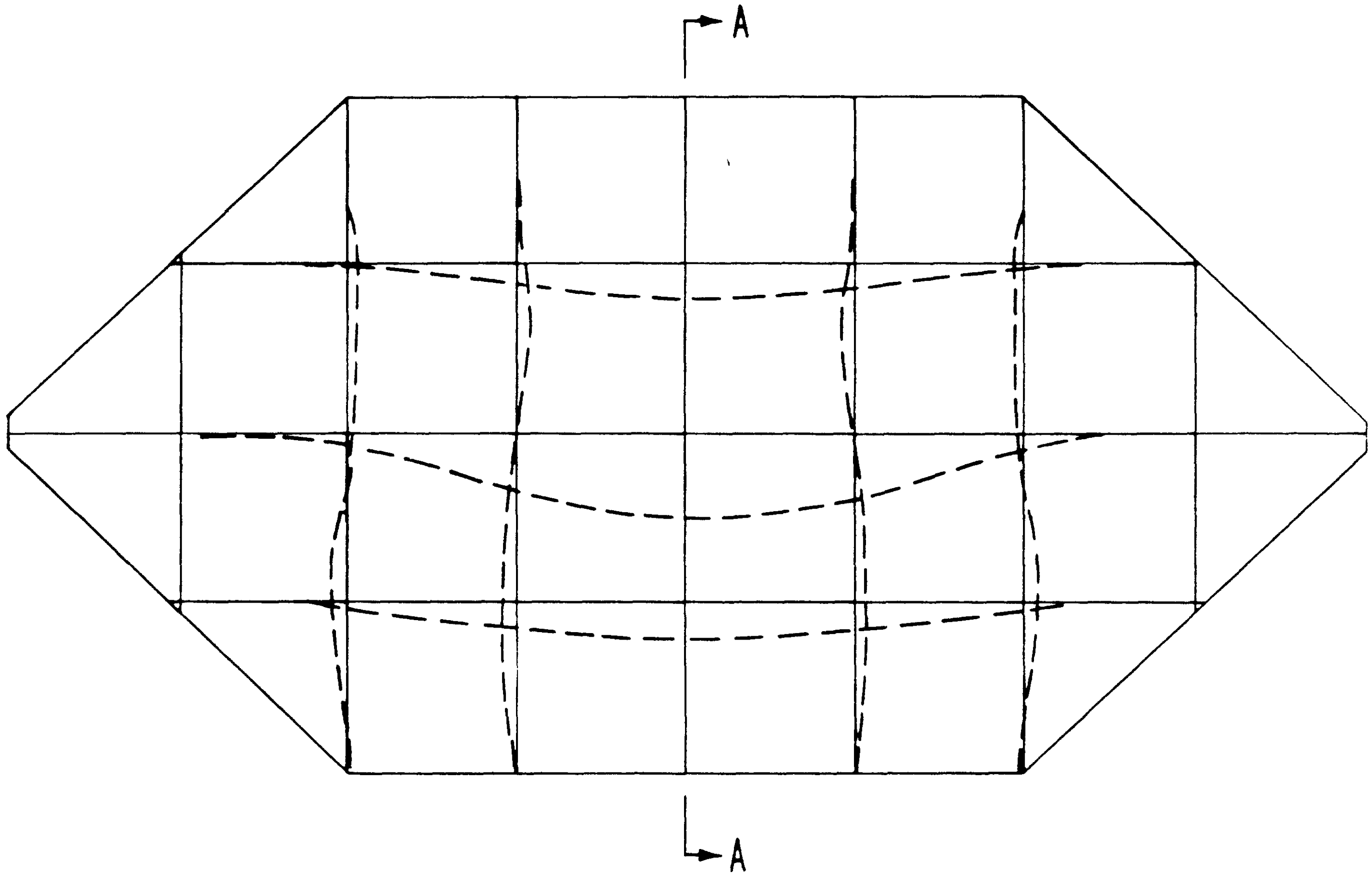
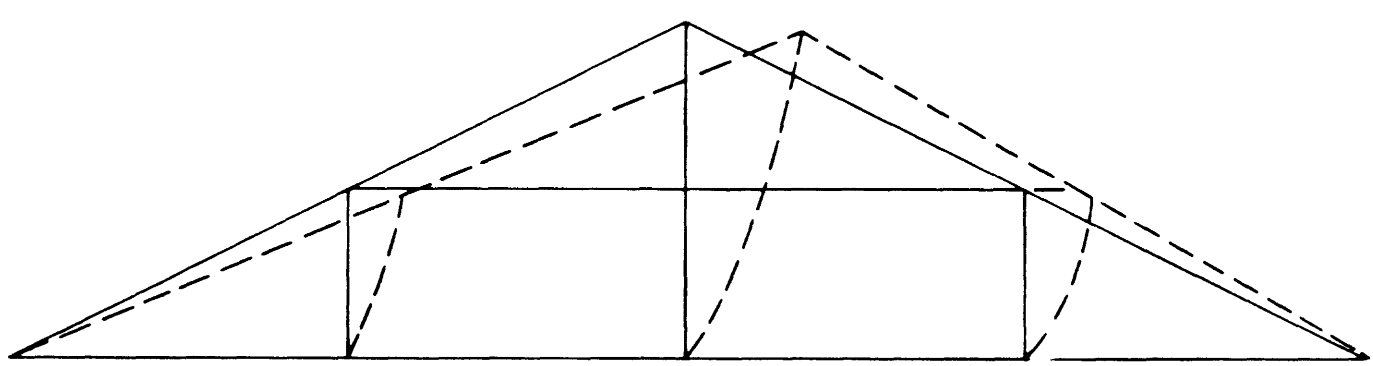


Figure 1. "Ideal" Earth Dam





SECTION A-A

Figure 2. General Shape of First Symmetric Transverse Mode for "Ideal" Earth Dam

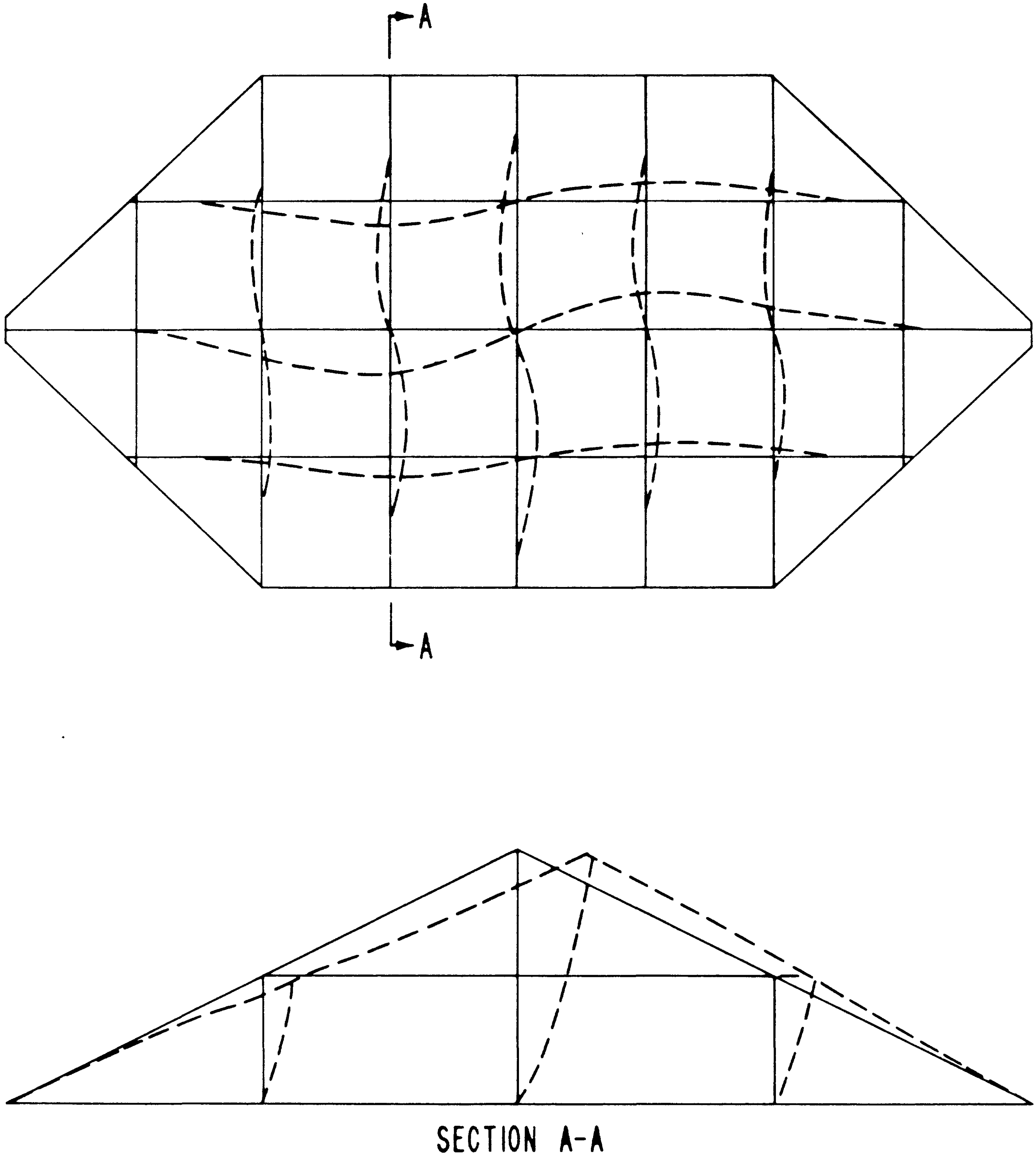


Figure 3. General Shape of First Anti-Symmetric
Transverse Mode for "Ideal" Earth Dam

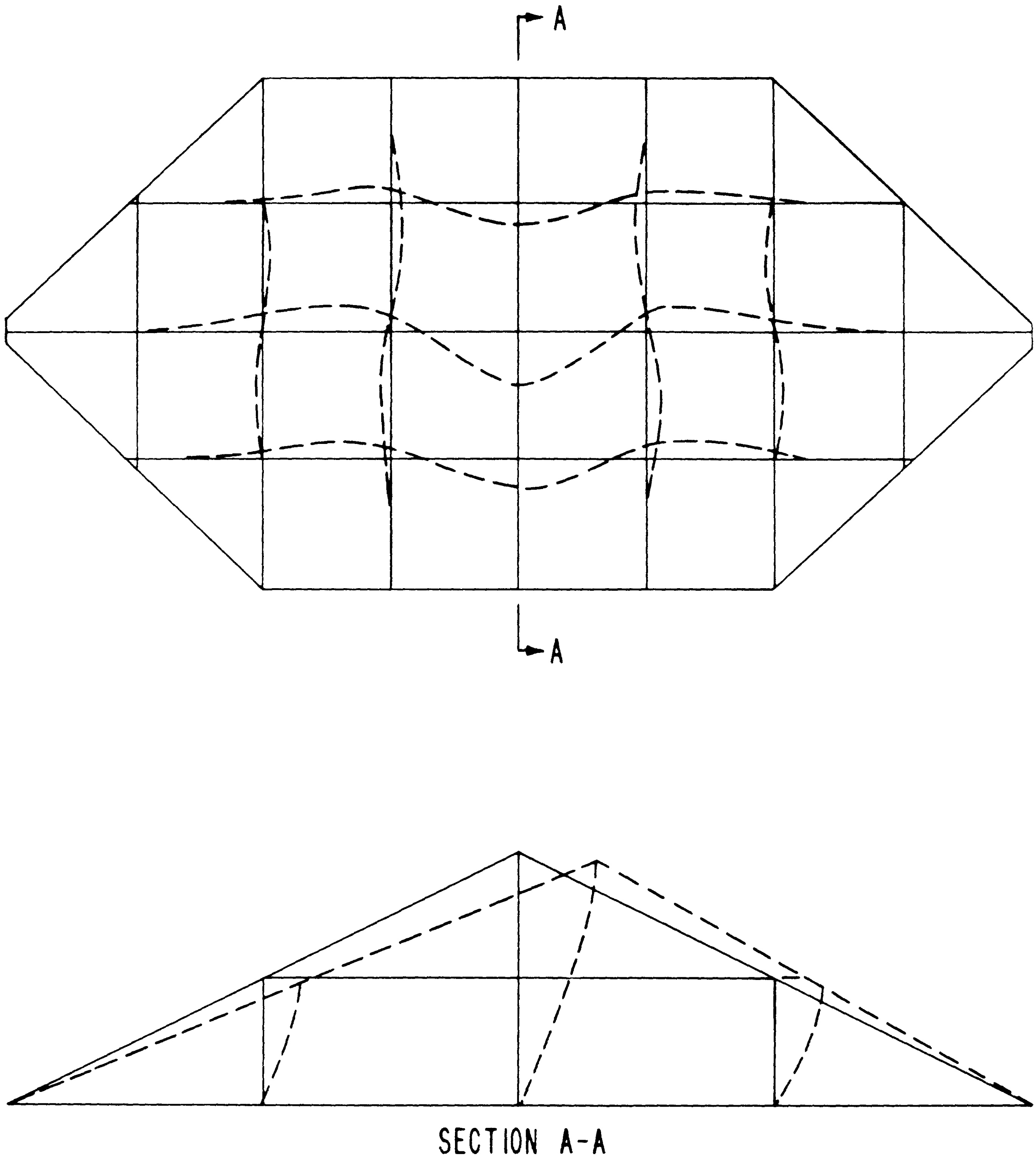
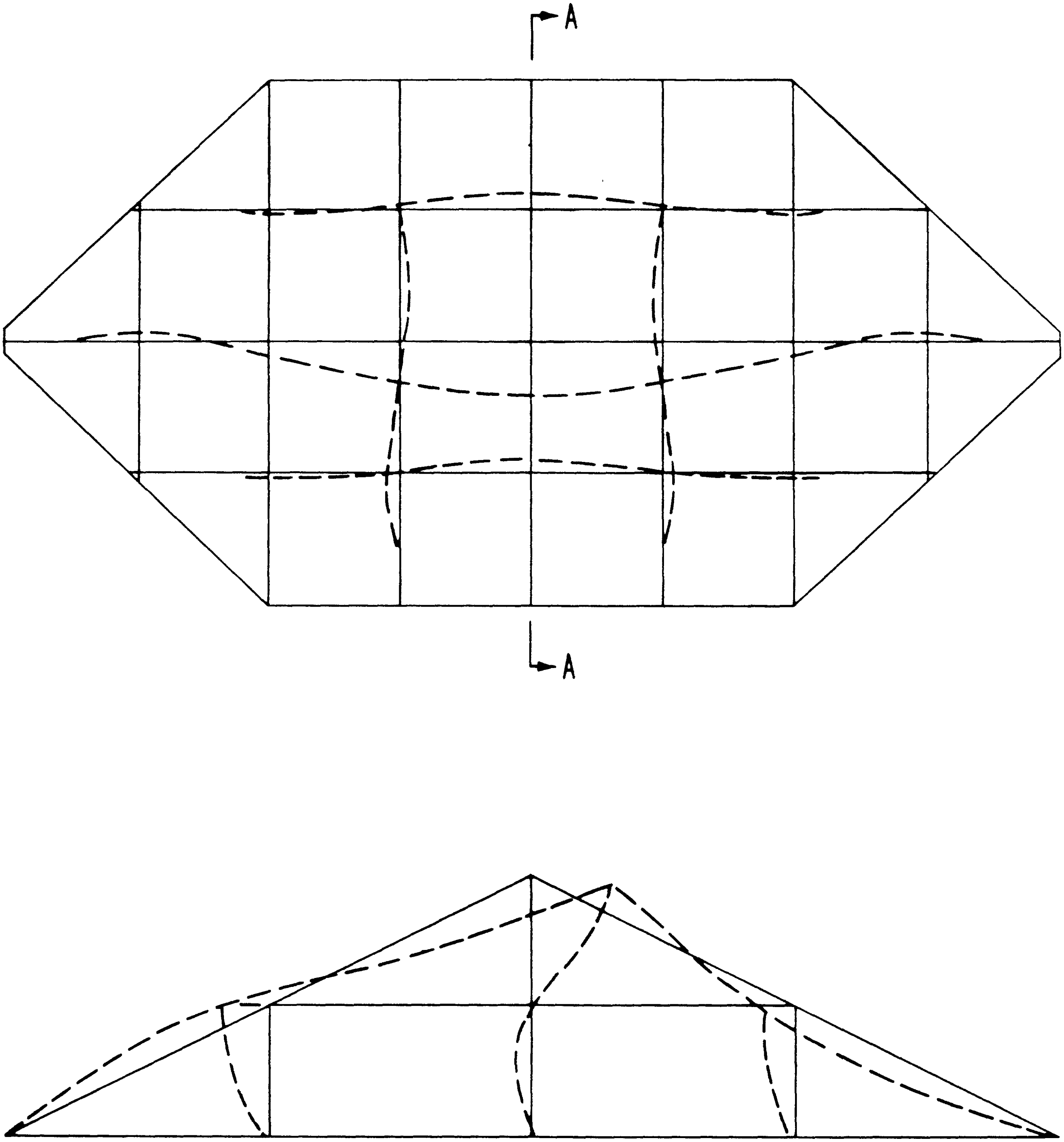
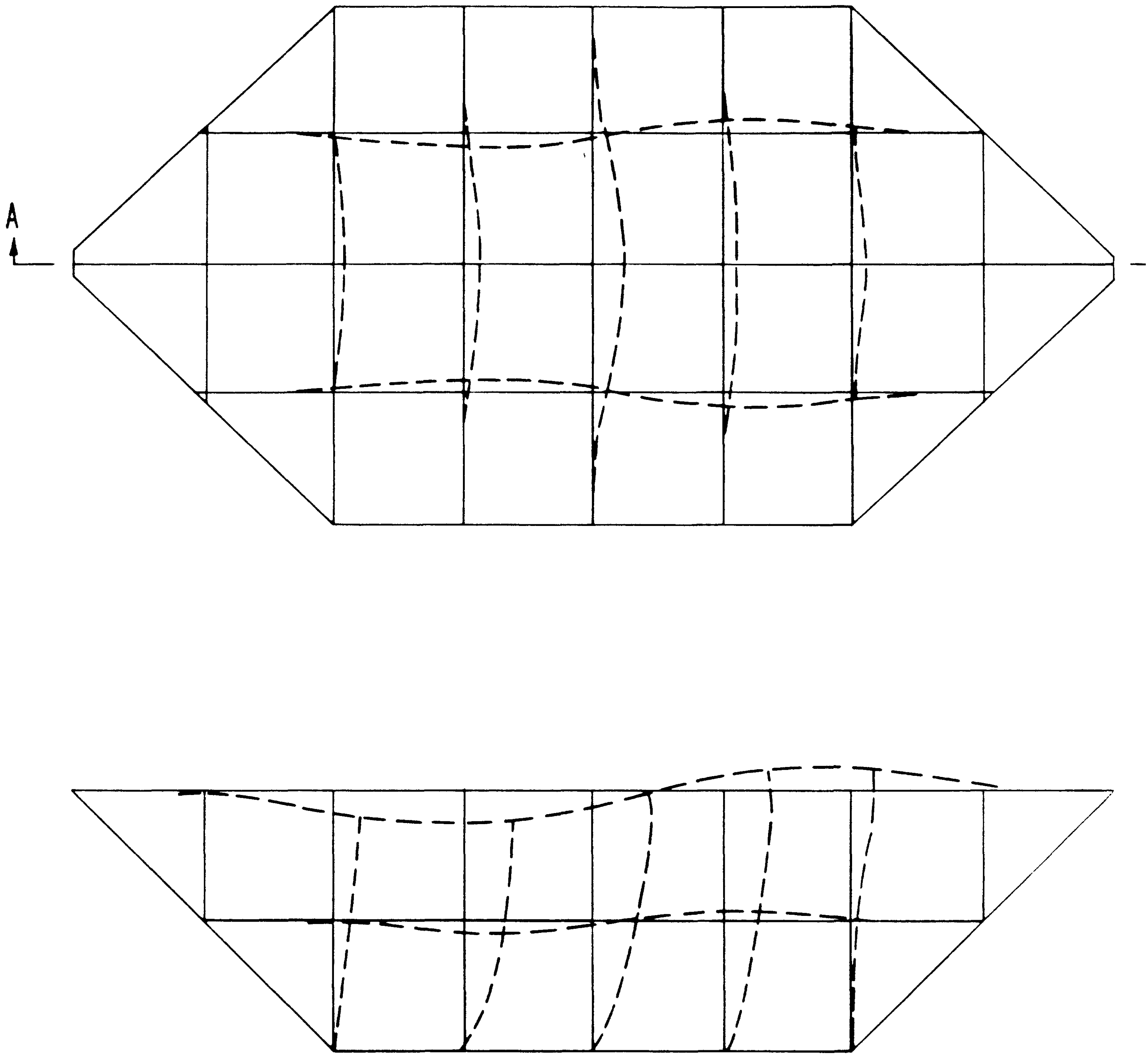


Figure 4. General Shape of Second Symmetric Transverse Mode for "Ideal" Earth Dam



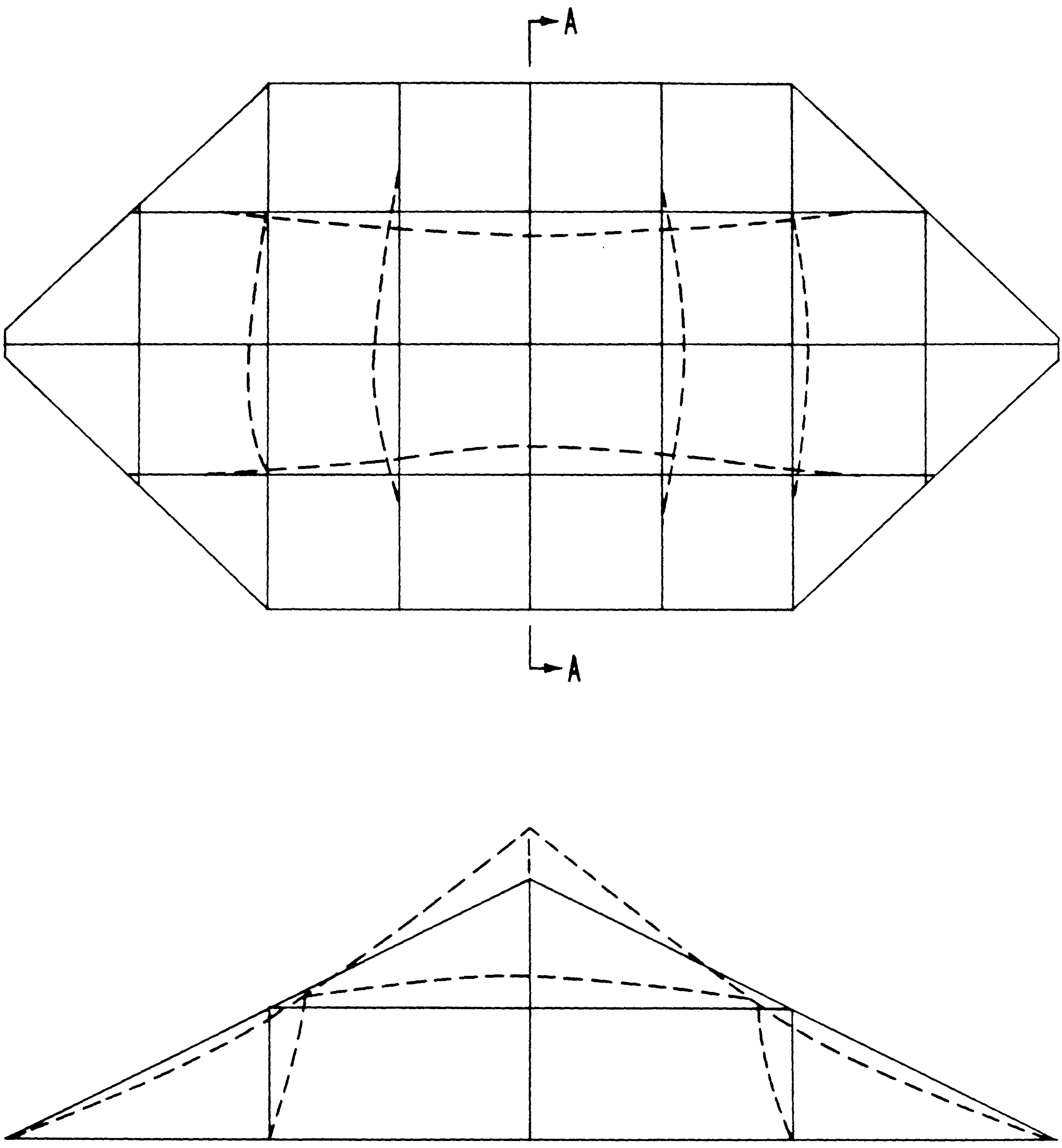
SECTION A-A

Figure 5. General Shape of Symmetric Transverse Mode with Nodal Point over Hieght for "Ideal" Earth Dam



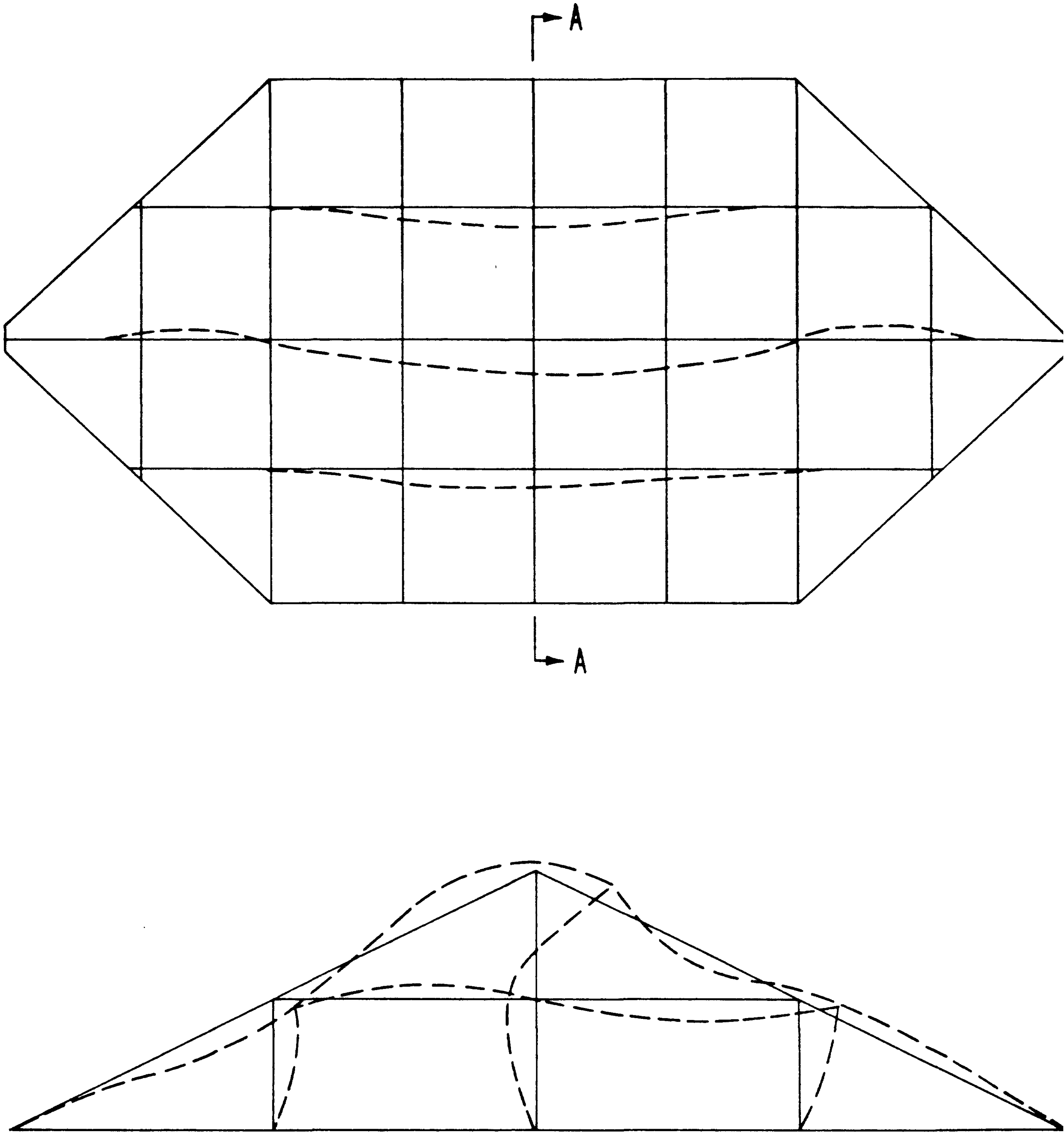
SECTION A-A

Figure 6. General Shape of First Longitudinal Mode for "Ideal" Earth Dam



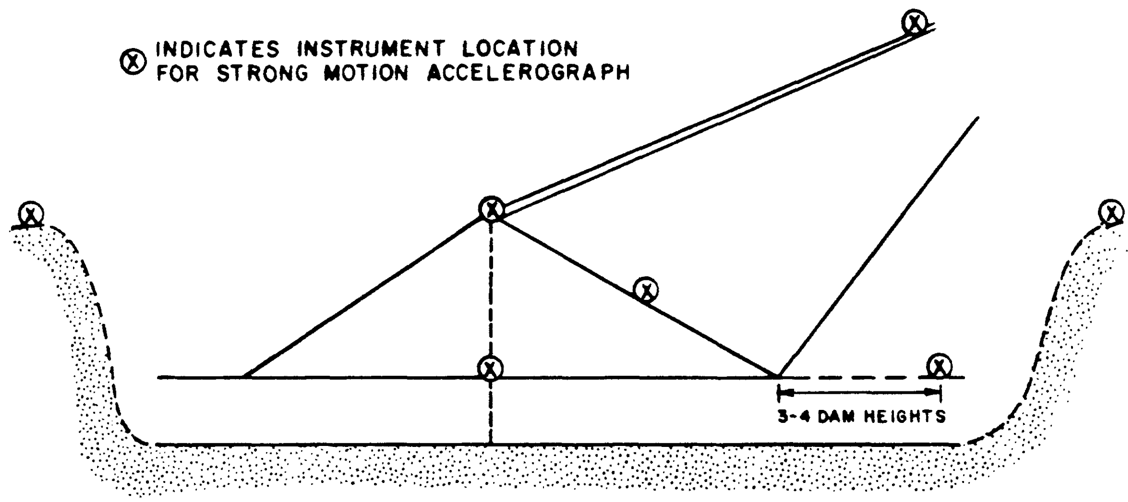
SECTION A-A

Figure 7. General Shape of First Vertical
Mode for "Ideal" Earth Dam



SECTION A-A

Figure 8. General Shape of First Rocking
Mode for "Ideal" Earth Dam



REQUIREMENTS FOR DIFFERENT CATEGORIES OF INSTRUMENTATION

CATEGORY	INSTRUMENTATION
A ABSOLUTE MINIMUM,	1 INSTRUMENT ON ABUTMENT (PROVIDED ABUTMENT MOTIONS NOT INFLUENCED BY LOCAL TOPOGRAPHY; OTHERWISE ANY LOCAL RELATIVELY FLAT ROCK OUTCROP) 1 INSTRUMENT ON CREST OF DAM
B DESIRABLE MINIMUM,	2 INSTRUMENTS ON ABUTMENTS (USE RELATIVELY FLAT LOCAL OUTCROP IN LIEU OF ONE ABUTMENT LOCATION IF ABUTMENT MOTIONS LIKELY TO BE INFLUENCED BY TOPOGRAPHY) 2 INSTRUMENTS ON CREST (AT DIFFERENT EMBANKMENT HEIGHTS, ONE AT MAXIMUM EMBANKMENT HEIGHT)
C DESIRED NORMAL	2 INSTRUMENTS ON ABUTMENTS (AS IN B ABOVE) 2 INSTRUMENTS ON CREST (AS IN B ABOVE) 1 INSTRUMENT ON DOWNSTREAM SLOPE (0.4 TO 0.5H ABOVE BASE OF EMBANKMENT) 1 INSTRUMENT ON FOUNDATION LEVEL IN FREE FIELD DOWNSTREAM (IF SOIL)
D DESIRED FOR MORE COMPLETE COVERAGE	2 INSTRUMENTS ON ABUTMENTS (AS IN B ABOVE) 2 INSTRUMENTS ON CREST (AS IN B ABOVE) 1 INSTRUMENT ON DOWNSTREAM SLOPE (AS IN C ABOVE) 1 INSTRUMENT IN FREE FIELD DOWNSTREAM (AS IN C ABOVE) 1 INSTRUMENT AT FOUNDATION LEVEL ON AXIS OF EMBANKMENT (IF SOIL FOUNDATION)

Figure 9. Strong-motion Instrument Locations for Earth and Rockfill Dams (WES, 1974)

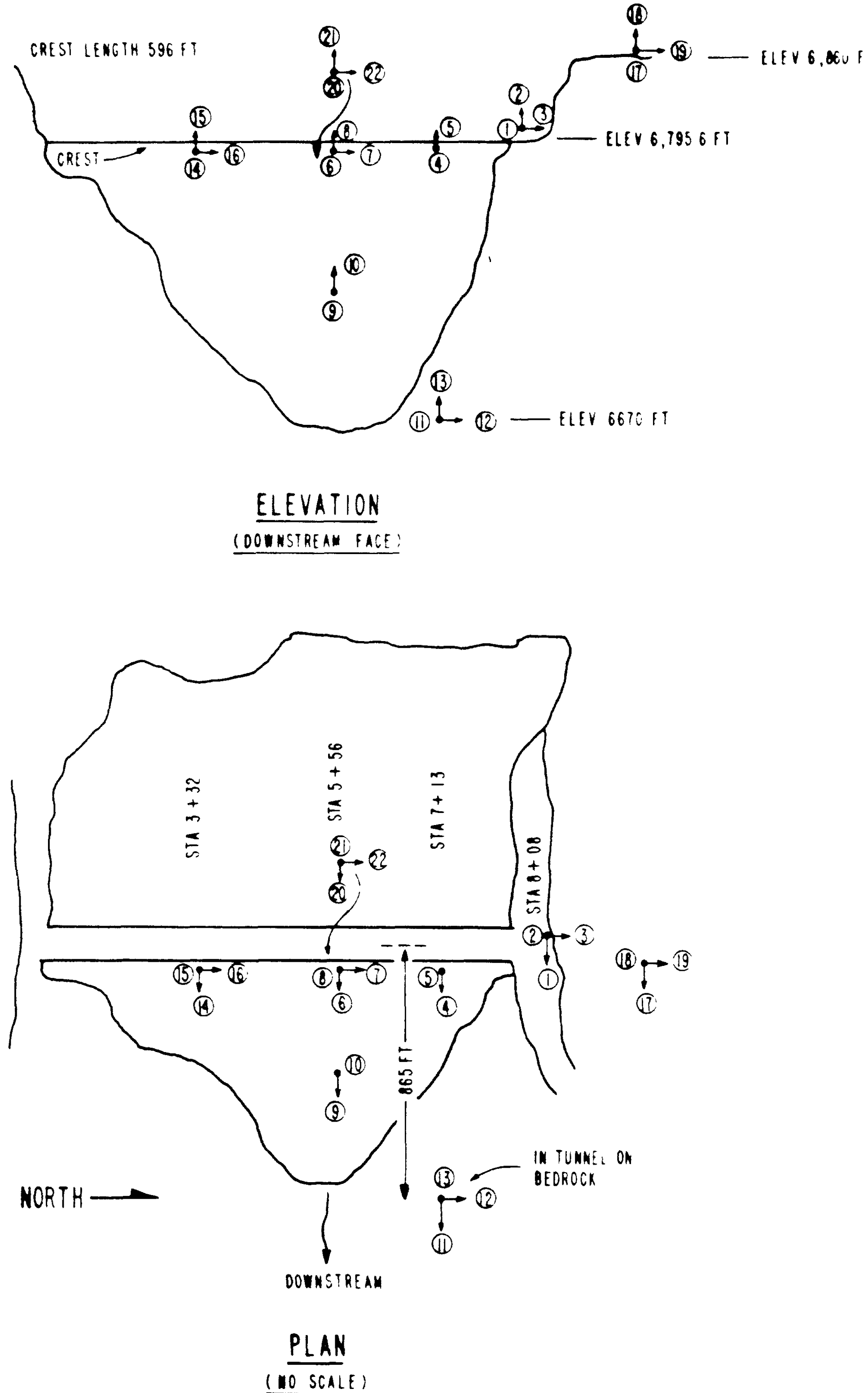


Figure 10. Long Valley Dam, Strong-Motion Instrumentation Scheme (Turpen, 1980) (Accelerometer Locations and Orientations selected by J. D. Ragsdale of CDMG)

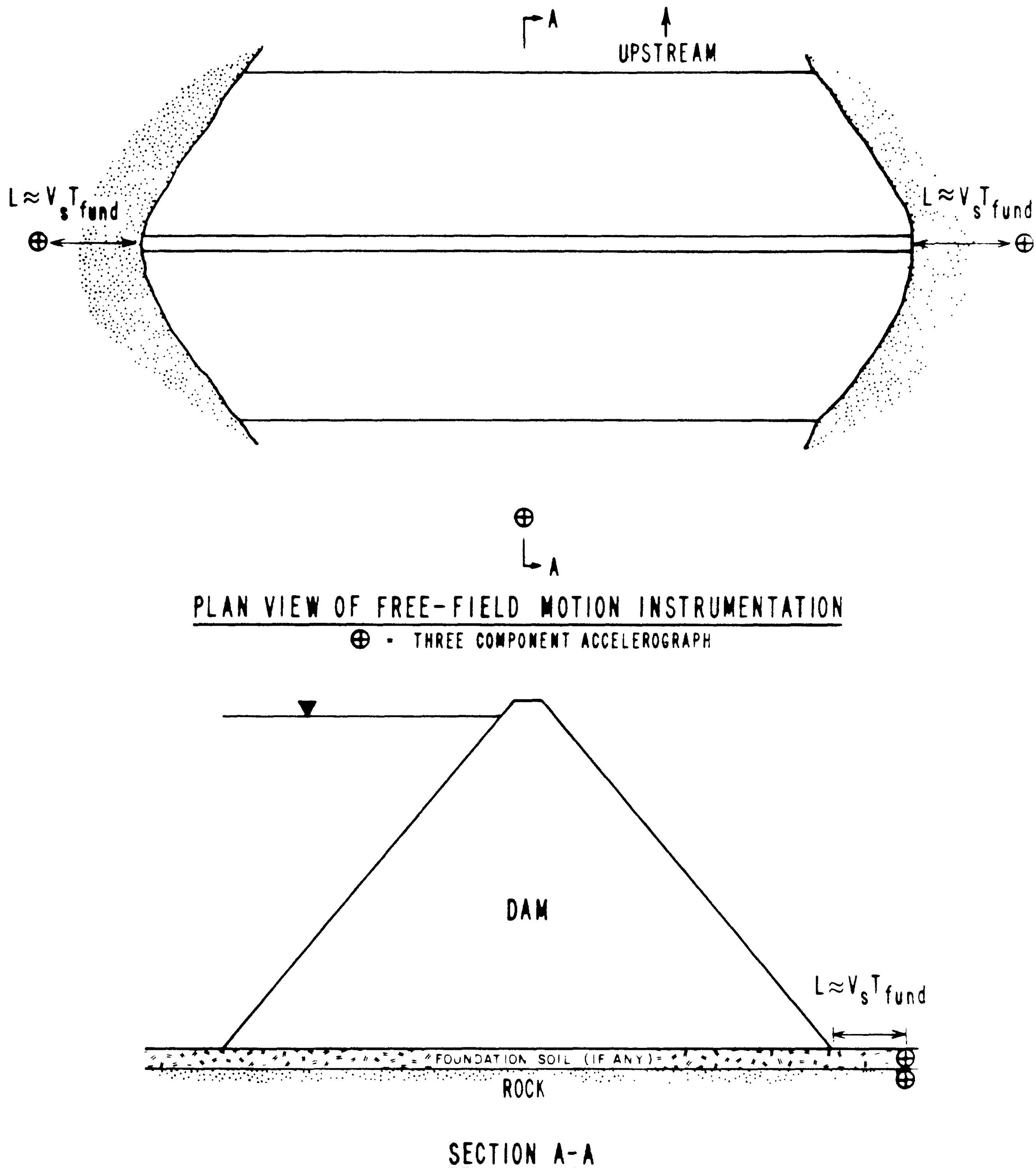


Figure 11. Proposed Instrumentation for Recording Free-field Motions Near "Ideal" Earth Dam

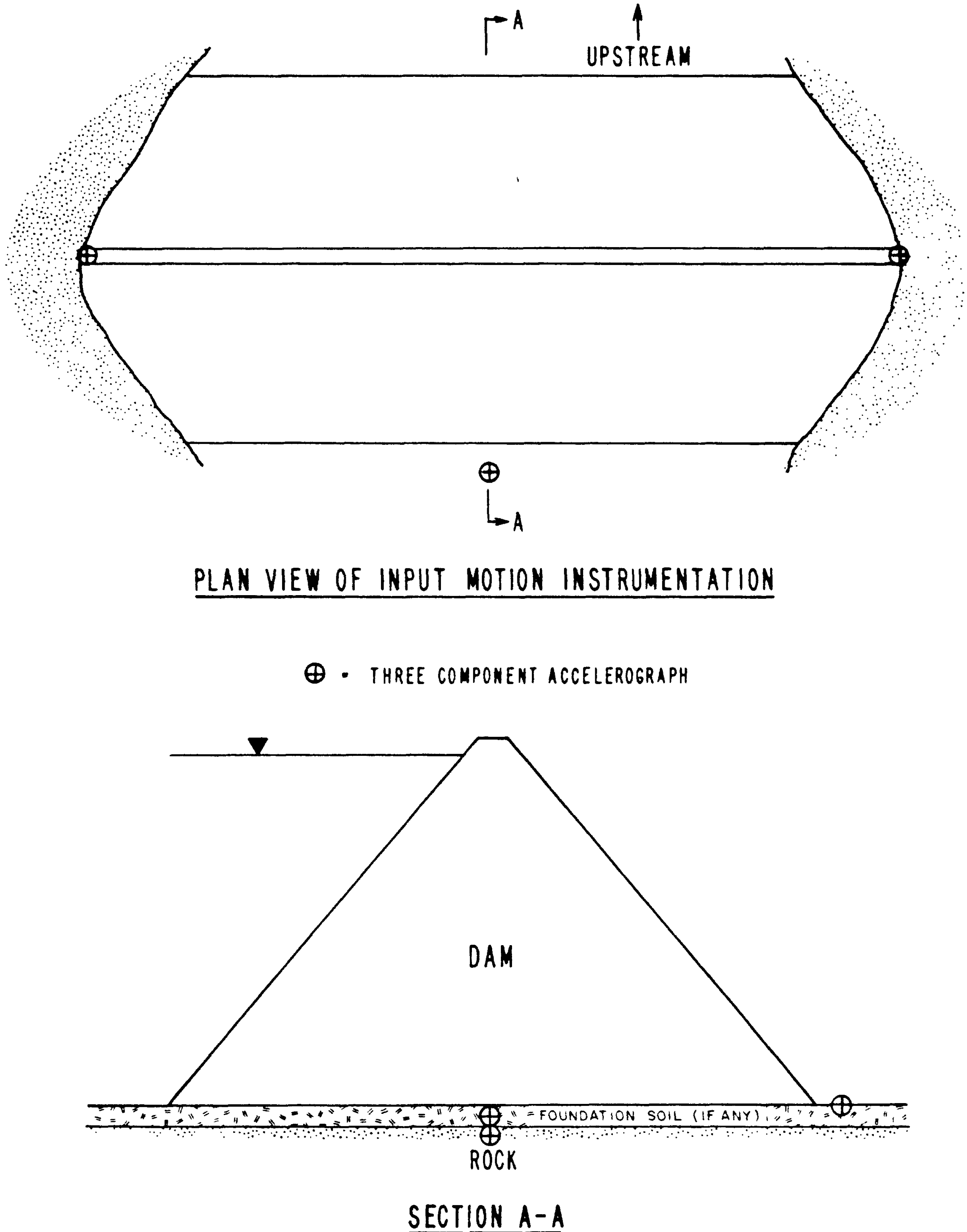


Figure 12. Proposed Instrumentation for Recording Input Motions to "Ideal" Earth Dam

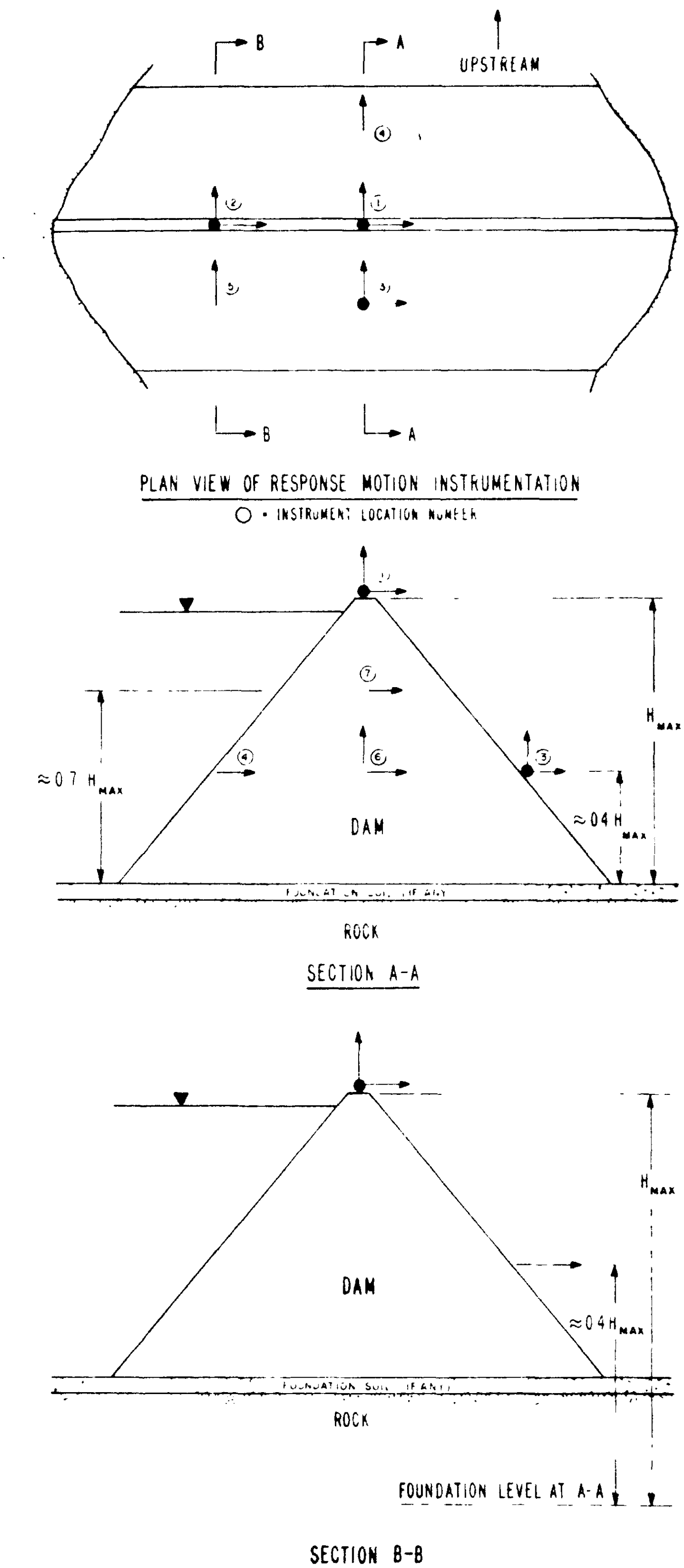
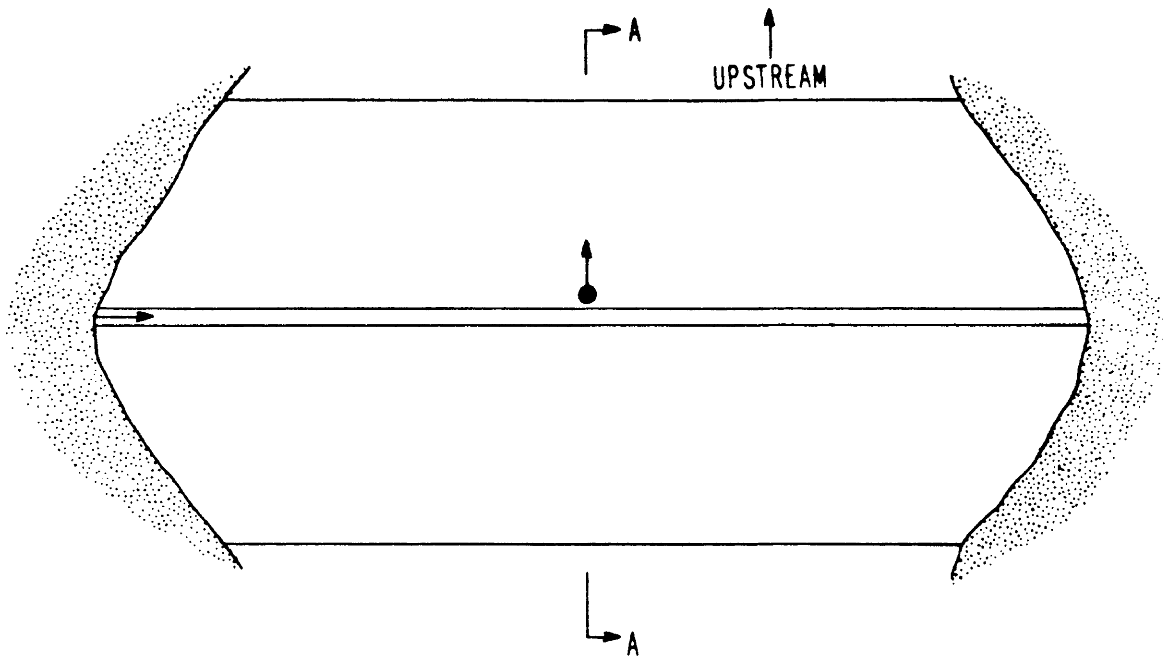


Figure 13. Proposed Instrumentation for Recording Response Motions of "Ideal" Earth Dam



PLAN VIEW OF FAILURE MOTION INSTRUMENTATION

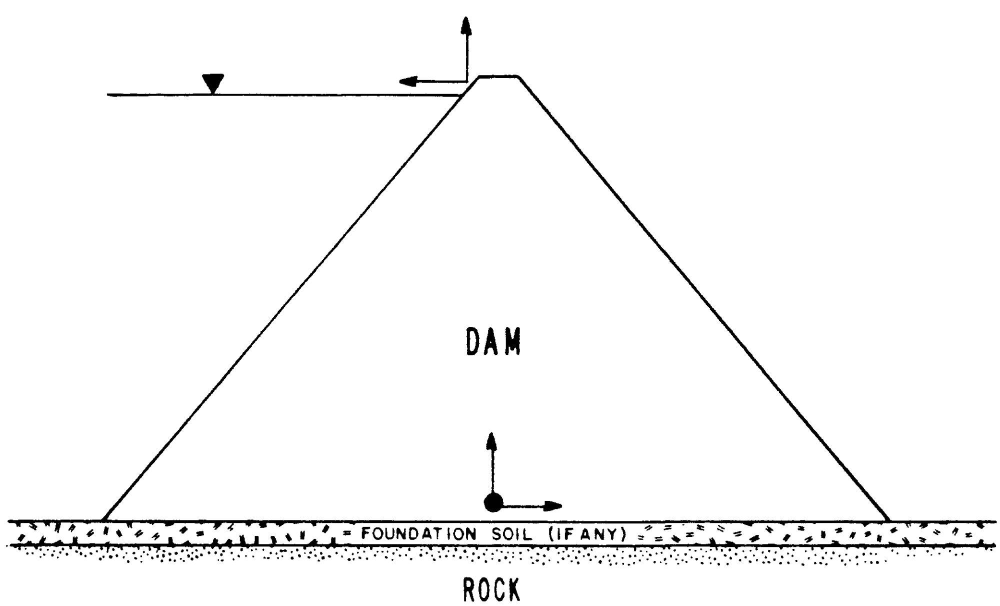


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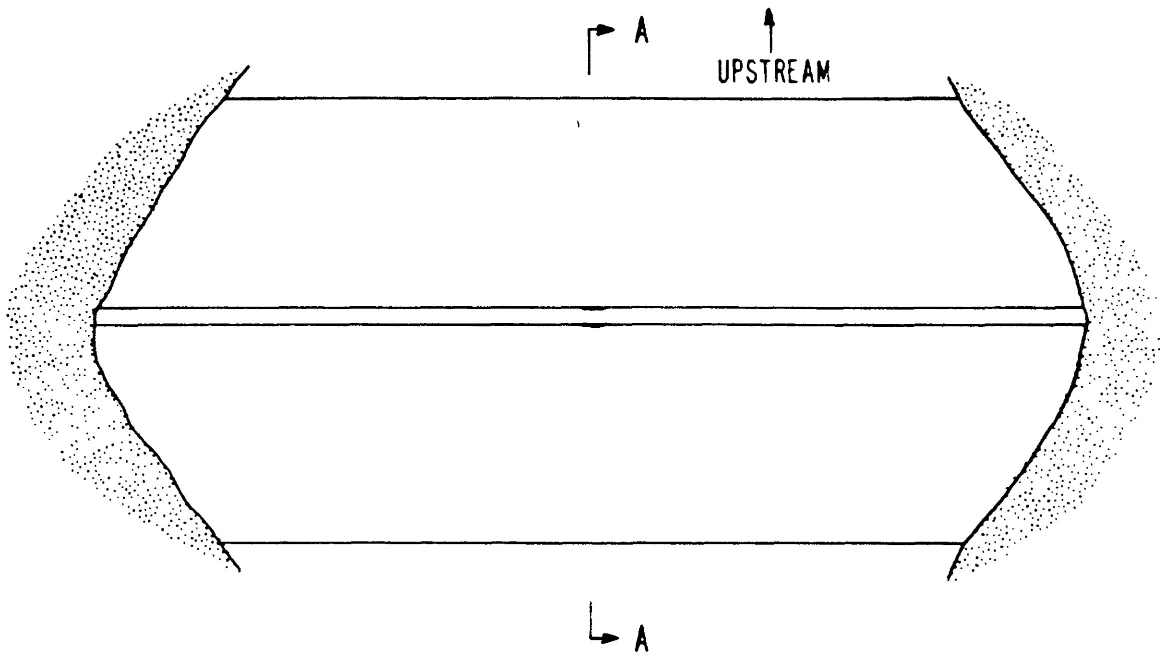
Figure 14. Proposed Instrumentation for Recording Failure Motions of "Ideal" Earth Dam



PLAN VIEW OF PORE PRESSURE INSTRUMENTATION

⊕ = PORE PRESSURE CELLS

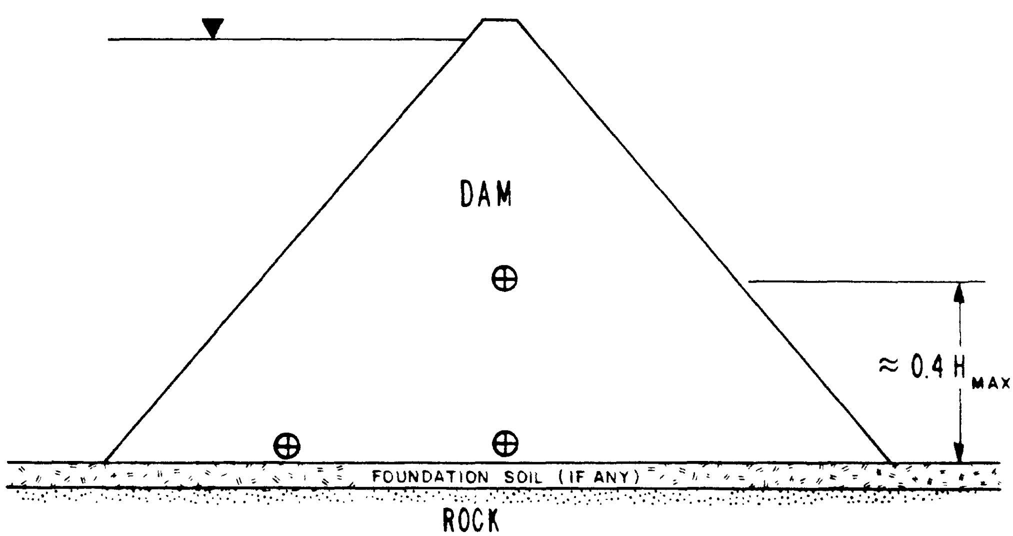


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Figure 15. Proposed Instrumentation for Recording Dynamic Pore Pressures within "Ideal" Earth Dam