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Example of design and construction of seismically resistant Reinforced Earth structures

Exemple de dimensionnement et de construction d'ouvrages en Terre Armée en zone sismique

Le dimensionnement de structures capables de résister à des tremblements de terre pose un difficile problème à l'ingénieur. La nature imprévisible des tremblements de terre ne permet pas d'utiliser une approche purement déterministe.
Une tentative de modélisation des tremblements de terre tenant compte de l'ensemble des réponses statistiques, afin de calculer les pressions dynamiques du sol et les déformations, a été appliquée au dimensionnement des principales structures en terre armée construites à la station terminale de Valdez de l'oéloduc Trans-Alaska.
Cette communication discute les concepts et les procédés développés en fonction de leur application possible au dimensionnement.

I. Introduction

Reinforced Earth structures to be built in seismically active zones require a somewhat different and more complicated design procedure from that normally associated with such structures. As in all earthquake engineering, of course, the objective of the seismic design procedure is to proportion the structure in such a way that it can survive without major structural failure the most severe earthquake predicted during the lifetime of the structure.

This paper presents the seismic design procedure used during the design and construction of five Reinforced Earth structures at Valdez, Alaska, the terminus of the Trans Alaska Pipeline. These structures were designed to resist an M8.5 earthquake. The design procedure developed incorporates statistical response spectra to model earthquake ground motions for earthquake magnitudes ranging from M4.0 to M8.5.

The seismic design of the Reinforced Earth structures was based upon extensive experience with the use and design of Reinforced Earth structures around the world; results of a major program of research and testing conducted by an independent agency; and modifications developed by The Reinforced Earth Company during the design and construction of the actual structures.

The research and testing program, sponsored in the United States by the National Science Foundation with the assistance of The Reinforced Earth Company, was conducted at the University of California at Los Angeles from 1974 to 1977. This program studied the effects of horizontal and vertical harmonic motions as well as irregular accelerations on model walls, and the effects of explosive-induced motion on a full-scale prototype wall. In addition, first and second mode natural frequencies and damping characteristics were measured on several completed Reinforced Earth structures.

II. Valdez - An Overview

At the southern end of the Trans Alaska Pipeline lies the deep water, ice-free port of Valdez where an enormous and complex crude oil handling facility, representing an investment of 15 million construction man-hours and $1,100 million (U.S.), has been completed after three years of non-stop, around-the-clock effort. This complex, shown in Figure 1, was constructed on approximately 400 hectares and includes:

- Eighteen crude oil storage tanks each with a capacity of 510,000 barrels.
- Four tanker berths including the largest floating berth ever installed.

- The largest tanker ballast water treatment facility of its kind ever built.
- Sophisticated power generator, vapor recovery and safety systems, and a computerized operations control center for the entire pipeline system.

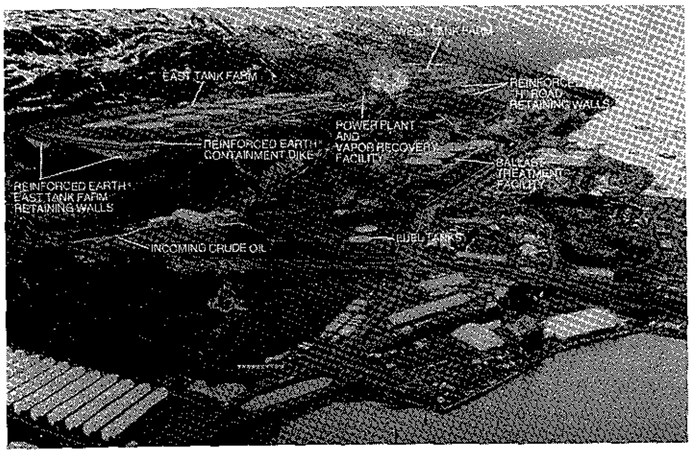


Figure 1: Overall View of Valdez Terminal

III. On-Site Engineering Concerns

Difficult geologic conditions and the tight physical constraints of the site presented the terminal design engineers with a problem in the construction of the embankment supporting a roadway. That roadway was to run west from the power plant and vapor recovery buildings up a 7 percent grade to the West Tank Farm.

The preliminary engineering, solution designed to meet the terminals strict seismic design criteria, called for extensive benching of the hillside and construction of a long, high embankment extending almost to the shoreline. This solution would have consumed most of the available land on the lower part of the site, and in addition to being an extremely time-consuming and expensive operation, would have adversely affected the master plan of vital terminal facilities. Similar problems existed, although not to the same degree, with embankments supporting access roadways to the East Tank Farm and with the East Tank Farm safety dikes.

During the winter of 1975-76, after construction of the terminal had begun, engineers of The Reinforced Earth Company met with the terminal contractors and the project's owners, the Alyeska Pipeline Service Company, to review the design requirements at the site and to develop alternate solutions to the high, rockfill embankments. Solutions developed replaced the long embankments with a series of Reinforced Earth retaining walls and a Reinforced Earth containment dike.

These Reinforced Earth solutions, shown in Figures 2 and 3, improved safety in the event of an earthquake, significantly reduced construction time by eliminating 350,000 cu.m. of rockfill, and provided an overall reduction in construction cost.

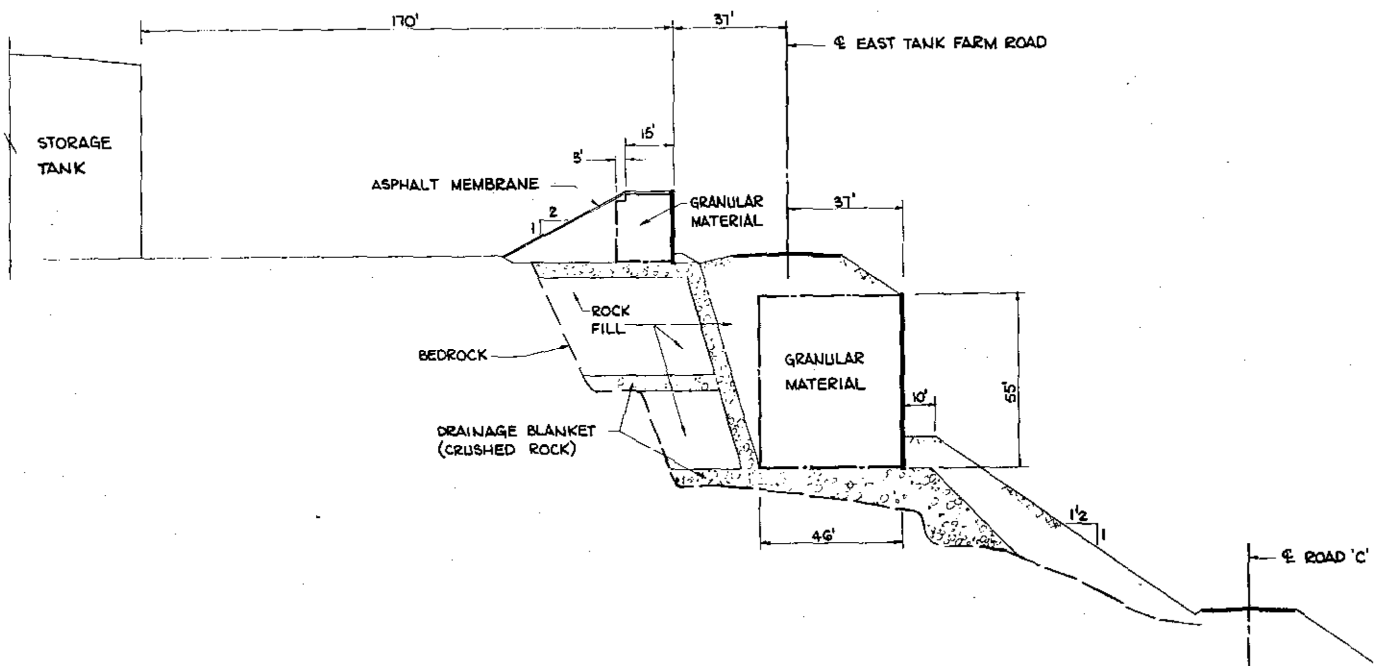


Figure 2: Typical Section of East Tank Farm

The aggregate surface area of the five structures constructed (Figure 4, 5 and 6) is approximately 12,000 sq.m. The height of three

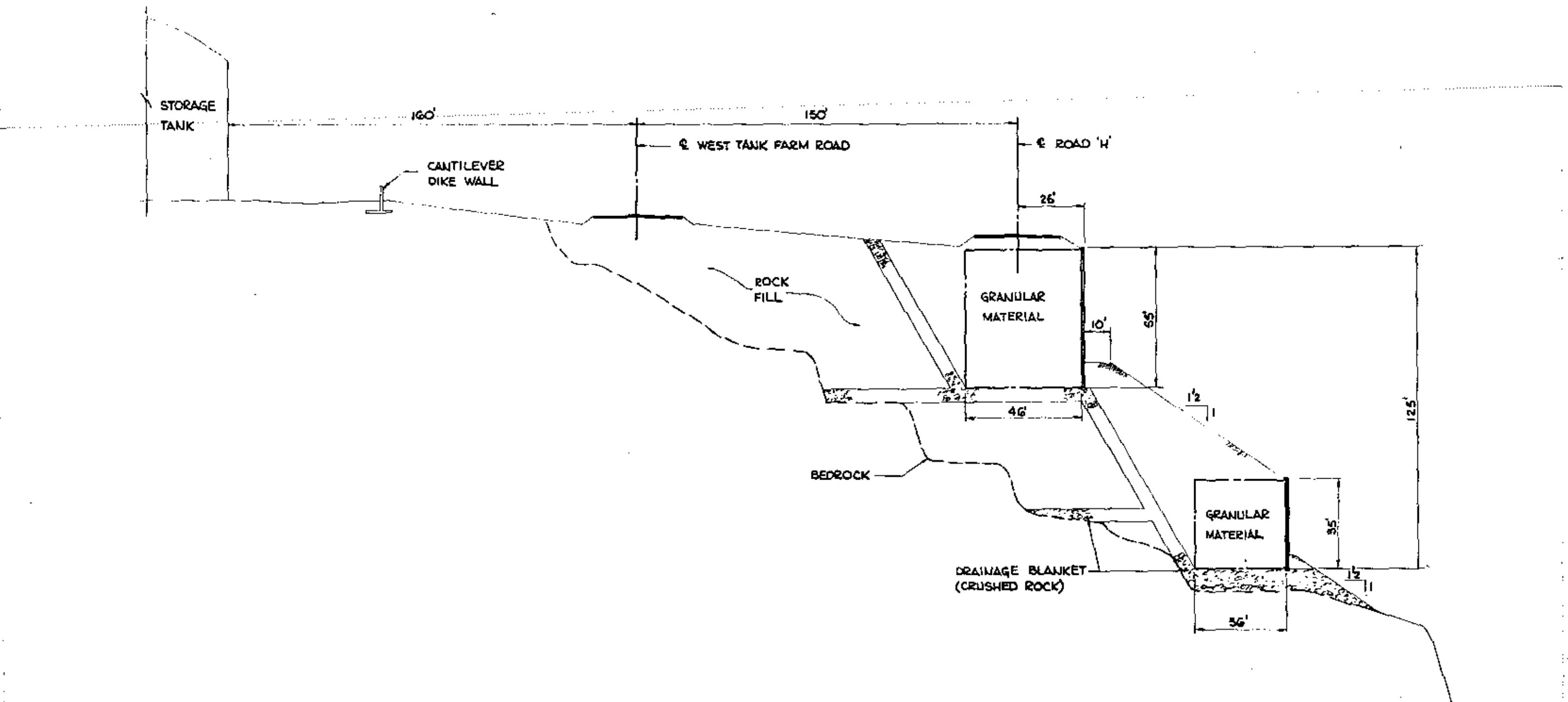


Figure 3: Typical Section of Road "H" Structures

of the structures exceeds 17 meters. Construction rates averaged 100 sq. meters per shift and on the East Tank Farm dike one crew completed nearly 300 sq. meters in a single shift (figures 4, 5, and 6).

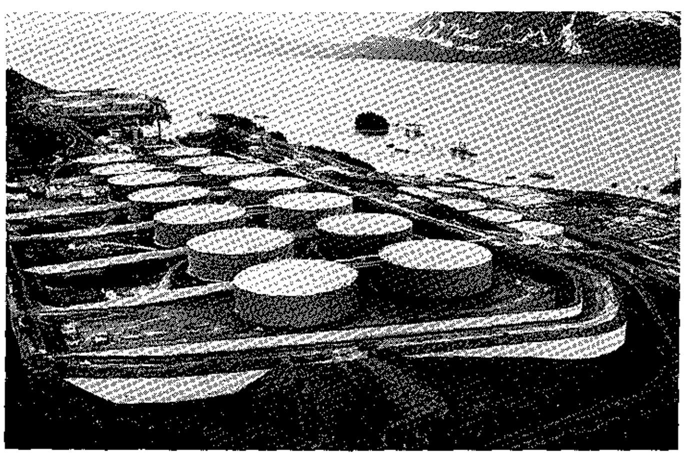


Figure 4: East Tank Farm

IV. Dynamic Design of Reinforced Earth

Engineers contend with great uncertainties in the design of structures to survive earthquakes. The random nature of earthquakes prevents the use of a purely deterministic design approach. Additional uncertainties related to soil-structure interaction and difficulties in adequately modeling the structure combine to make an uncertain problem even more difficult.

During a seismic event, the total dynamic forces in a structure are assumed to be the sum of the static forces acting before the event plus dynamic forces generated during the seismic event. Static forces in a Reinforced Earth wall are calculated using procedures developed by The Reinforced Earth Company[1] and proven in over 2,200 actual installations. Dynamic forces generated during a seismic event are due to the relative acceleration of the inertial mass of The Reinforced Earth structure. These dynamic forces are calculated using procedures initially developed in the UCLA research and testing program[2] [3] and modified by The Reinforced Earth Company.

Figure 5: Road "H" Retaining Walls

Response spectrum techniques with empirically-defined parameters are the basis for the design procedure used to calculate dynamic forces. This response spectrum technique mathematically uncouples the equations of equilibrium of a multiple degree-of-freedom (DOF) system such that it can be treated as an assemblage of single DOF elements. Each of these elements corresponds to a particular natural or resonant mode of vibration of the N-DOF system.

The response spectrum technique calculates only the maximum response of each single-DOF element. The contribution of each single-DOF element to the response of the multiple-DOF system is defined by a participation factor unique to that mode. The response of the multiple-DOF system is then assumed to equal the sum of the maximum model responses multiplied by their respective participation factors. As the maximum responses for each modal single-DOF element may not occur at the same instant of time, the calculated response is an upper bound for the actual response of the multiple-DOF system.

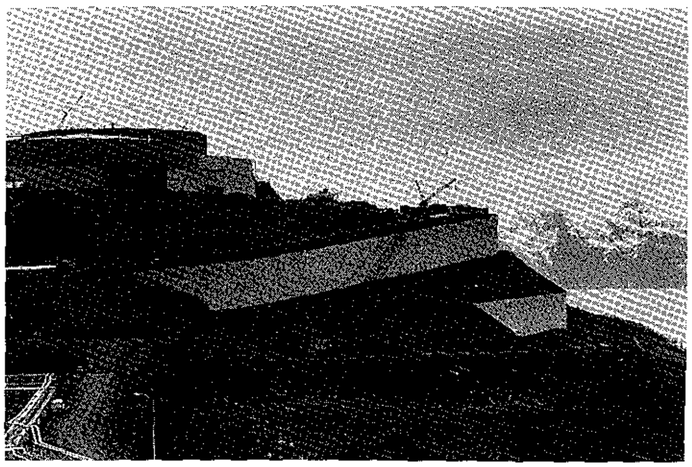


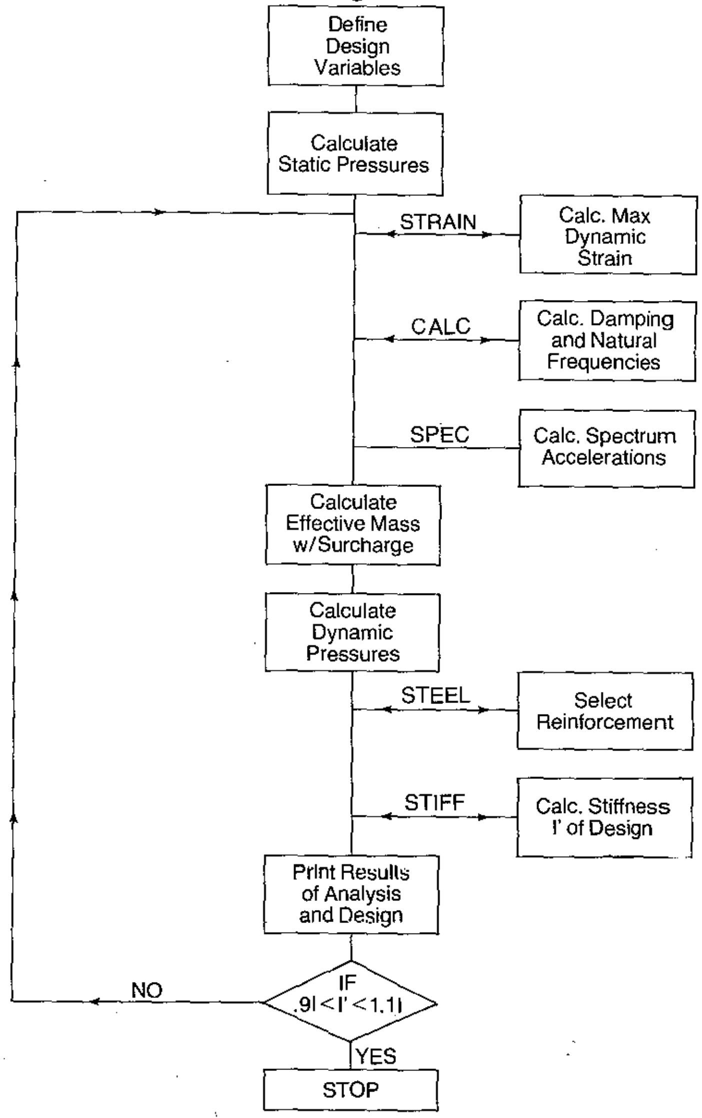
Figure 6: Road "H" Retaining Walls

An important concept which resulted from the research work was the observation that the total dynamic force, the distribution of dynamic forces, and the dynamic strain are influenced by the density and geometry of the reinforcing strips. An empirical stiffness coefficient was developed to quantify the influence of the density and geometry of the reinforcing strips.

The dynamic stiffness coefficient is defined as the second moment of the force required to cause yielding of the strip about the base of the wall. In low walls the yield force of the strips will be governed by the tie pullout. In high walls, the yield force of the strips may be limited by the yield stress of the strips.

Empirical relationships developed using the stiffness concept showed that the relative stiffness of one wall with respect to another was more important than the absolute magnitude of this stiffness parameter. Thus, if the response of a wall with a given strip configuration is known, then the response of a second wall of arbitrary strip configuration can be determined.

The dynamic design procedure developed by UCLA and The Reinforced Earth Company has been presented in detail in previous publications. The procedure is presented in flow chart form in Figure 7. How this procedure was applied to the actual design of the structures at the Valdez terminal is discussed in the following sections.



Flow Chart of Seismic Design Procedure
Figure 7

Typical Design Procedures

For illustrative purposes the design section shown in Figure 8 represents a typical wall designed for this project. In accordance with the design flow chart, the analysis begins by defining the usual geometric and soil backfill design variables and calculating the developed static pressures by conventional methods (1) (4). The effect of dynamic forces is calculated first by determining the maximum dynamic strain based on the maximum tolerable horizontal displacement for this type of structure for an originally assumed stiffness. This stiffness is consistent with a density and length of reinforcing strips required to resist the imposed static forces only. From the geometry, the resonant frequencies for the first two ambient transverse modes f_1 and f_2 can be obtained directly from data previously published(3). The strained natural frequencies can be subsequently obtained from a developed relationship between the dynamic strain and the ratio of strained and ambient frequencies. Using the Design Contingency Spectra for this project (M8.5 earthquake), developed by the terminal designers and a damping of 26%, deemed appropriate, first (Sa_1) and second (Sa_2) spectral accelerations can be calculated using conventional seismic methodology.

The effective mass of a Reinforced Earth structure is calculated by defining the participatory area that would move laterally in a seismic event. It is defined as:

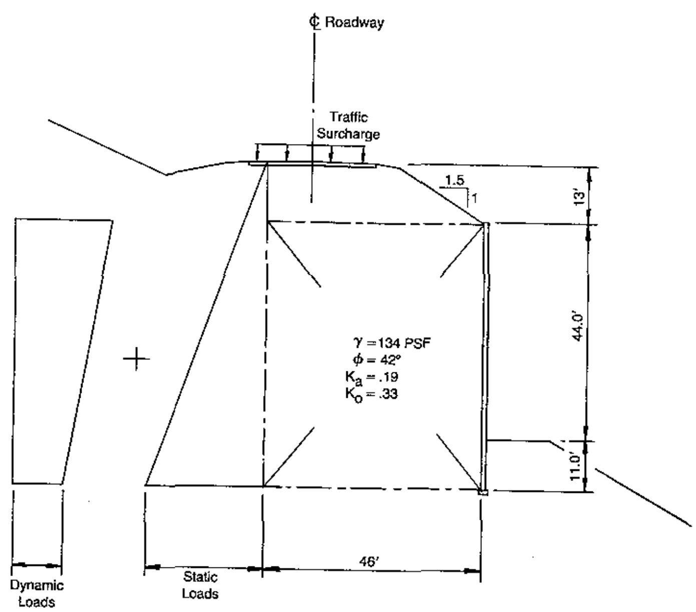
$$M_{EFF} = \frac{0.75\ Ko\ \gamma\ H^2}{g}$$

The total dynamic lateral force is equal to:

$$F = (Sa_1 + 0.2\ Sa_2)\ M_{EFF}$$

where Sa_1 and Sa_2 are the previously calculated first and second spectral accelerations. The lateral dynamic earth pressure distribution can be obtained at midheight as the product of the reciprocal of the reference stiffness defined as a wall having minimum reinforcements for static loads, multiplied by the ratio of total dynamic lateral force to the design height. At the base of the wall, the dynamic earth pressure distribution is equal to the ratio of the midheight distribution to the reference stiffness. Thus, as the wall is made stiffer, the dynamic pressure distribution reduces to an inverted triangle distrubtion commonly assumed in pseudo-static design methodology. The balance of the design consists of conventional steel selection to resist the developed combined pressure distribution and the calculation of the structure's stiffness.

If the thusly designed structure stiffness (I') falls in the range of 0.9 I < I' < 1.1 I, where I is the initially assumed normalized stiffness, the design can be considered optimized. If the design structure stiffness (I') is significantly greater than the assumed one (I), the design is conservative and may be recycled for better economy, by using the calculated normalized stiffness (I') of the design wall. This will reduce the dynamic lateral earth pressures yielding a wall not as stiff. If the design structure stiffness (I') is significantly less than the assumed one (I), the lateral dynamic earth pressures have been underestimated and the resulting wall is not sufficiently stiff and would be subject to unacceptable dynamic strains. The calculations in this case would be recycled by assuming a higher initial stiffness which would yield higher lateral dynamic pressures.



Typical Section And Design Parameters

Figure 8

For the design section in Figure 8, the calculations of the pertinent seismic parameters can be summaried as follows:

Summarized Calculaions of Pertinent Seismic Parameters

Estimated Peak Dynamic Strain		=	0.5%
Low Strain Natural Frequencies	F_1	=	2.27 Hz
	F_2	=	6.0 Hz
Strained Frequencies	F_1	=	0.8 Hz
	F_2	=	2.1 Hz
Spectral Acceleration	Sa_1	=	0.5 g
	Sa_2	=	0.72 g
Total Effective Mass	M_{EFF}	=	131,000/g lbs./ft.
Dynamic Pressures	a) at top of wall	=	1.26 KSF
	b) at midheight	=	0.97 KSF
	c) at bottom	=	0.61 KSF

Table 1
Summarized Calculations
of Pertinent Seismic Parameters

Conclusions

The method of calculation presented above was used to design all of the Reinforced Earth structures at the Valdez Terminal.

The effect on structure design of added dynamic forces is to increase the density of reinforcing strips required near the top of the structure: strip lengths remain substantially equal as in static design. The use of conventional pseudo-static approximations for development of dynamic forces would yield a roughly equivalent design, but would not estimate the magnitude of dynamically induced deflections where deflection considerations may govern the design.

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