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Design Criteria for Structures Subject to Repeated Limited Strains

Critères de dimensionnement pour les structures soumises à des déformations répétées et limitées

Bemessungskriterien für Tragwerke, die wiederholten begrenzten Verformungen ausgesetzt sind

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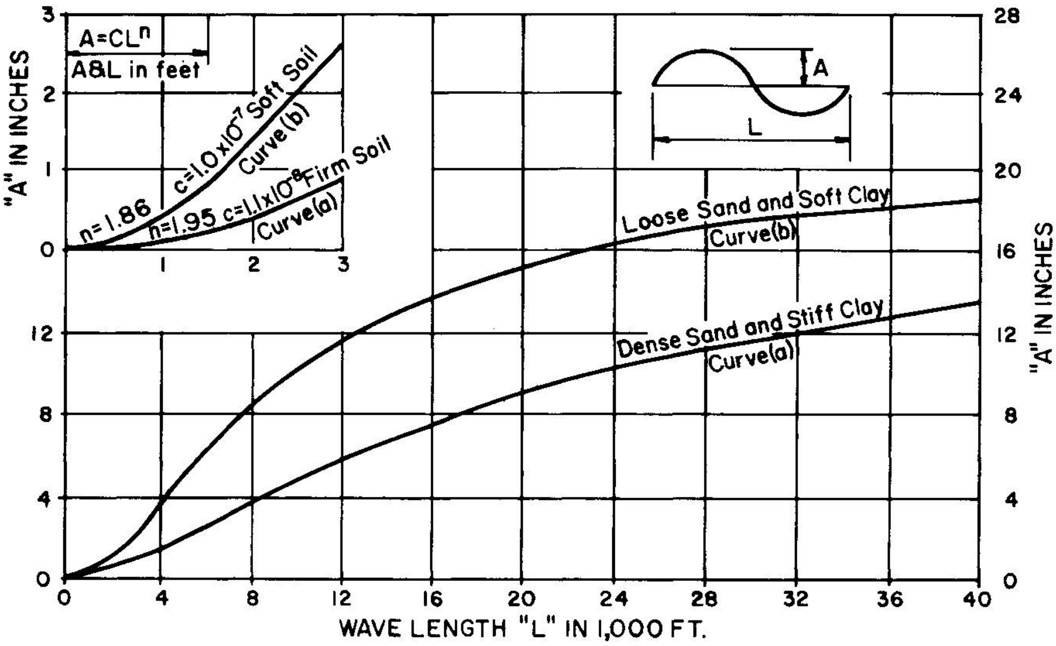
Most investigations of periodic structural phenomena have concentrated on repetition of a defined load or force function, and have attempted to deduce or observe the resulting deformations. This approach is appropriate for transient gravity loadings, such as live loads of transport vehicles.

However, for many important problems, the imposed periodic phenomenon is a displacement or strain, and what is sought is the resulting structural reaction. The largest classification of such problems is those relating to earthquakes, whose effects have been too often described in terms of inertial reaction forces, and too infrequently in terms of motions and deformations, which are the primary seismic phenomena.

In the case of buried structures, such as tunnels, subways, and underground chambers, it is obvious that the seismic deformations imposed on the structure must be the same as those occurring within the surrounding earth. The design process then consists of defining the seismic deformations of the earth, and checking the ductility of the structure against the imposed repeated strains. In this case, the <u>ultimate</u> deformability is of only academic interest – it is necessary and sufficient merely to determine that the structure has <u>sufficient</u> deformability.

As an example of the application of this principle, the earthquake design criteria for subways for the San Francisco Bay Area Rapid Transit System (the BART project) may be cited (Ref. 1). The basic definition of the seismic deformations was provided by Dr. George Housner of the California Institute of Technology, in the form of a spectrum of wave lengths vs. amplitude (Fig. 1), based on many years of observations of California earthquakes.



BART DESIGN EARTHQUAKE SPECTRUM

Fig. 1

From this basic spectrum, a graph of curvature of the seismic ground waves may be constructed, and from this the elastic strains imposed by the earthquake on any buried structure may be determined. For the conditions of the BART project, the maximum unit strain resulting from ground curvature was:

$$\xi = 5.2 \frac{A}{L}$$

where ξ = unit strain, inch/inch
A = amplitude of seismic wave, feet
L = length of seismic wave, feet

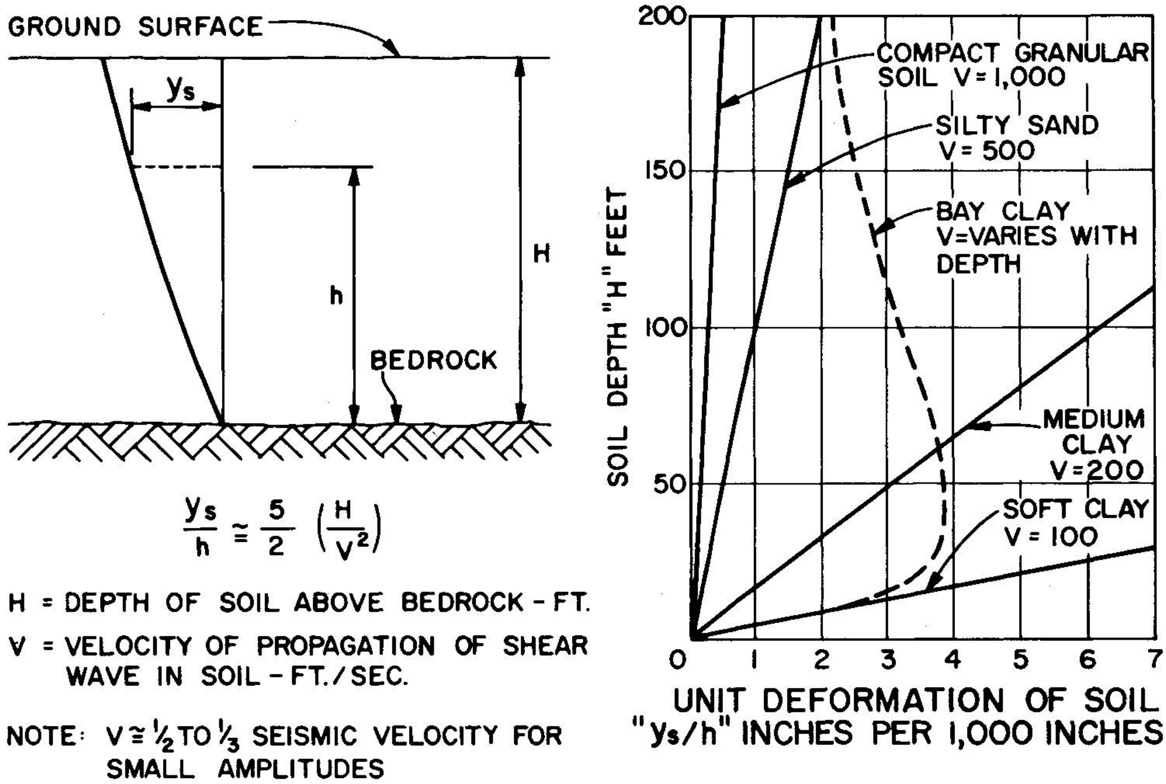
For a typical subway line structure, the maximum unit strain in the concrete walls was 52×10^{-6} in/in, which is well below the strain limit for flexural rupture (see Fig. 2).

	LINE STRUCTURE		STATION BOX	
TYPICAL OVERALL WIDTH, W, FEET CRITICAL WAVE LENGTH, L=6W, FEET	35 210		70 420	
SOIL TYPE	DENSE SAND	SOFT CLAY	DENSE SAND	SOFT CLAY
AMPLITUDE–INCHES –FEET	0.0044 0.00037	0.025 0.0021	0.017 0.0014	0.090 0.0075
RADIUS OF CURVATURE, $R=\frac{L^2/4\pi^2 A}{5280}$, MILES	580	101	610	114
UNIT STRAIN INDUCED BY OBLIQUE WAVE, FOR ψ =32°, $\varepsilon=5.2\frac{A}{L}$, MILLIONTHS INCH/INCH	9	52	17	93
UNIT STRESS INDUCED, PSI FOR E= 4,000,000 PSI	36	208	68	372

EXAMPLES OF STRAINS DUE TO CURVATURE DISTORTION

Fig. 2

In addition to strain from direct curvature, a buried structure is also subject to shearing strains resulting from the lag of motion in the overburden behind that in the basement rock. The intensity of this shearing strain is determined by the depth of the overburden, its dynamic rigidity (measured by its seismic velocity), and the characteristics of the vibration of the rock. These may be reduced to a graph in the form of Fig. 3, again representing conditions on the BART project.



SHEARING DISTORTION OF GROUND
BART DESIGN EARTHQUAKE

Fig. 3

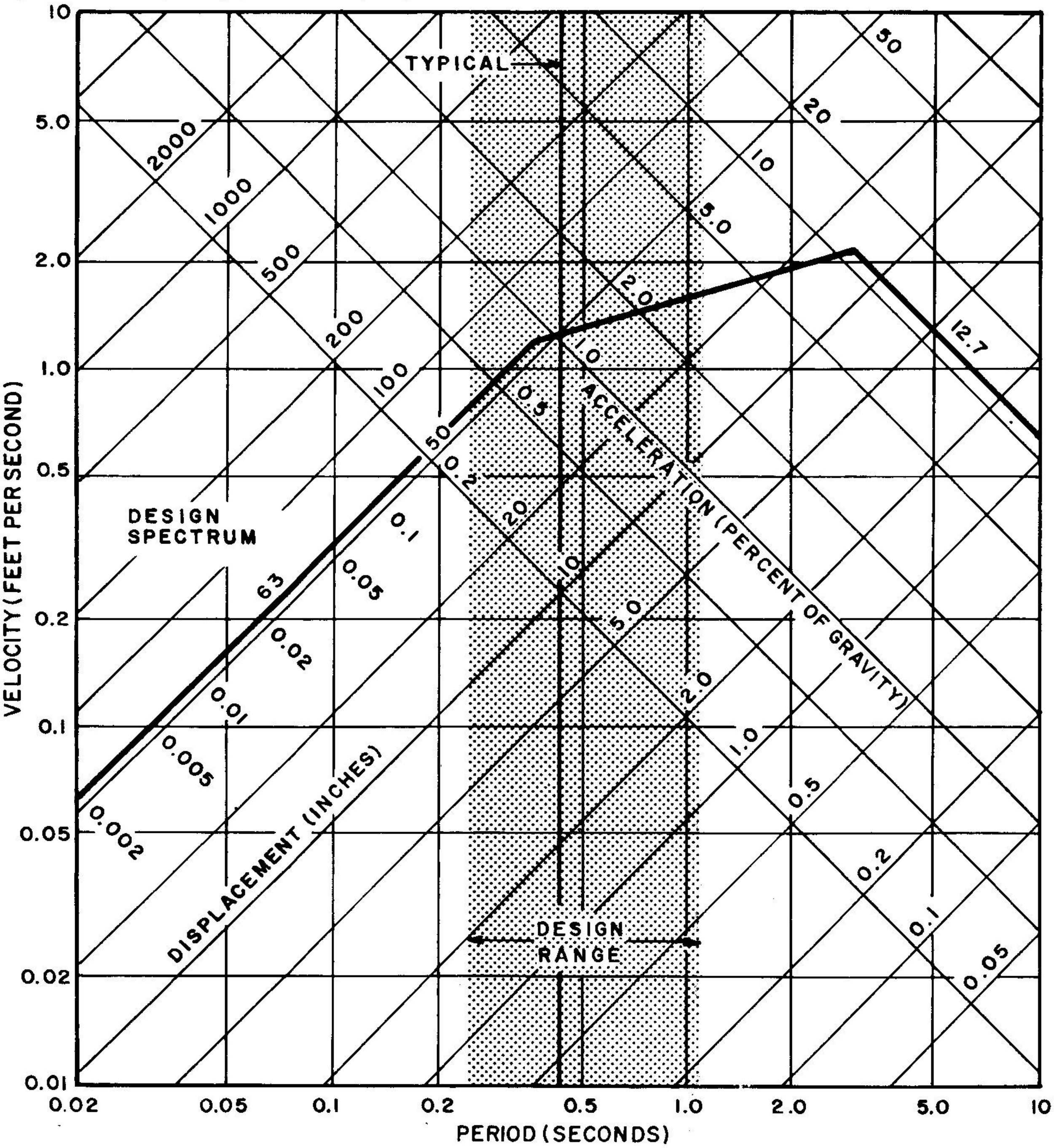
From such a graph, the shearing distortions imposed on a buried structure may be determined, and the design criterion is that the structure must retain its capacity to carry static loads and earth pressures, while subject to the repeated shearing distortions so defined. For the BART subway, this turned out to be no problem except in a few special cases in extremely soft soils. Further details are given in Ref. 1.

It is less obvious that similar principles apply to the aseismic design of many aboveground structures. The response of an elastic structure to earthquake excitation of its foundation is a function of its natural frequency of vibration. By limiting this natural frequency, the designer may control the amplitude of the vibratory response of the structure. The periodic strains imposed on the elements of the structure may thus be limited, and the design may proceed in a manner analogous to that for buried structures.

This principle may also be illustrated by reference to the BART project, particularly to the special seismic design criteria for the aerial structures, which consist of single-column reinforced concrete pier shafts supporting concrete box girder superstructure spans.

The basic ground deformation spectrum for soft alluvium (Fig. 1) may be replotted in the form of Fig. 4, a four-dimensional plot of acceleration, velocity, displacement (or amplitude), and natural period of vibration as devised by Dr. N. M. Newmark of the University of Illinois. This graph represents the response of a single-degree-of-freedom oscillator to the vibrations of the BART design earthquake. Since the single-column pier supporting a concentrated superstructure mass may be closely represented by an inverted pendulum (a single-degree-of-freedom oscillator), the amplitude of its response may be controlled by limiting its natural frequency of vibration.

A high frequency of vibration (or low period) was ensured by providing stiff pier shafts. The specific criteria adopted for the BART aerial structure piers were that in response to the design earthquake the reinforcing steel should not be stretched to more than twice the yield strain, and the compressive strain in the concrete should not exceed 0.0038 in/in (Ref. 2). These criteria determined the allowable lateral deformation (or amplitude of vibration) for any combination of pier height and width. Figure 4 then indicates the acceleration imposed by the design earthquake, and the limiting pier shaft frequency (or stiffness) required.



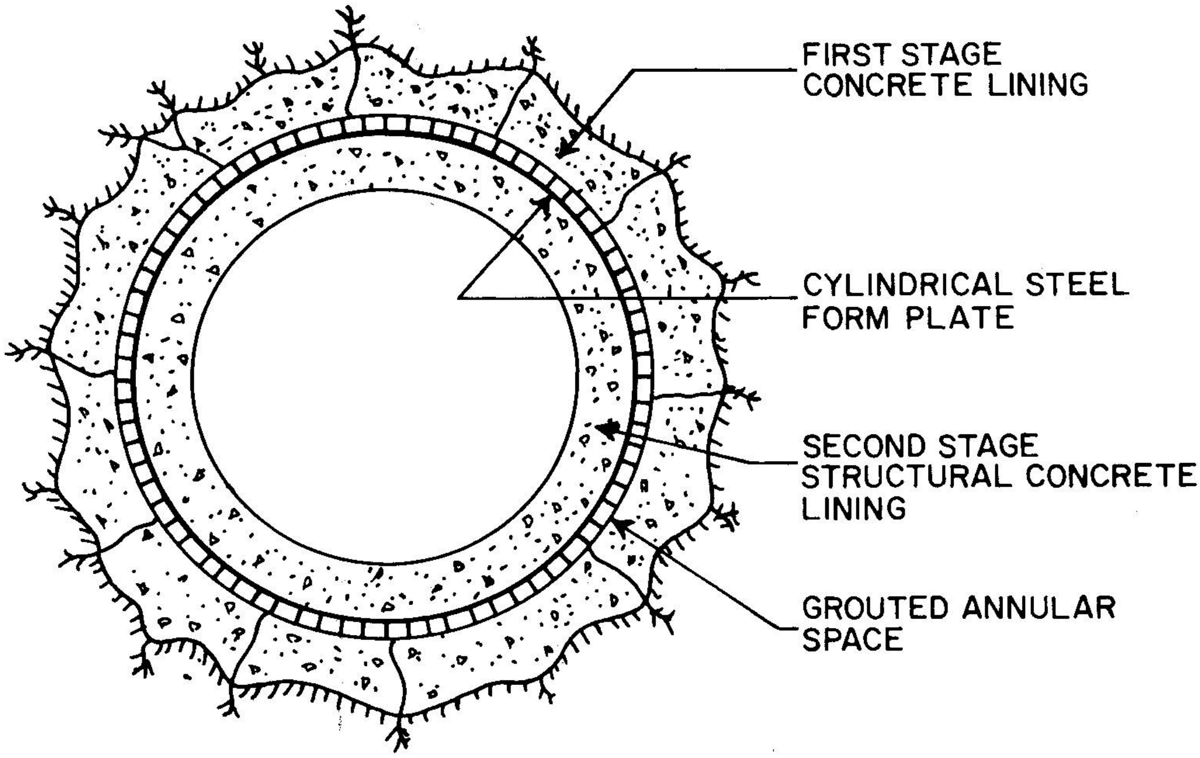
BART AERIAL STRUCTURE RESPONSE SPECTRUM

Fig. 4

A different structural problem involving repeated, limited strains occurs in hydroelectric projects, where it is necessary to design steel-lined penstocks encased in rock tunnels. The water pressure, which may be subject to wide and frequent fluctuations, is contained by the combined action of the thin steel lining and the surrounding rock. Considerable economic benefits could be realized by reducing the thickness of the steel lining, and allowing it to undergo repeated inelastic strains, which would be limited by the elastic reaction of the rock.

Unfortunately, a lack of practical experience with large-scale steel structures repeatedly strained into the inelastic range has inhibited designers from venturing into this unexplored territory, and current practice is to limit the strain in the steel liner under normal operating conditions to the elastic range. The confinement provided by the rock is recognized by increasing the steel working stress to about 3/4 of the yield strength (Ref. 3).

An interesting solution to this problem was devised by the designers of the Dez Dam in Iran (Ref. 4). The project includes steel-lined buried penstocks operating under a head of approximately 200 meters. The penstock tunnels were lined in two stages (see Fig. 5). First, the rough excavation was lined with a moderate-strength concrete to produce a smooth cylindrical cavity. Within this, a thin cylindrical steel form plate was erected, leaving an annular opening between it and the outer concrete lining. A high-strength concrete interior lining was then placed and cured. Finally, high pressure grout was introduced into the annular opening, cracking the outer lining to force grout into the surrounding rock, and prestressing (or pre-straining) the inner structural lining. The principle here is to introduce an initial compressive strain equal to or greater than the tensile strain anticipated under working conditions.



DEZ DAM PRESSURE TUNNEL
SCHEMATIC CROSS SECTION

Fig. 5

The principles of designing for limited strains are relatively easily set forth. To establish quantitative design criteria, it will be necessary to accumulate performance history records on actual projects where these principles have been used. All designers having experience in this field can contribute to the profession by publicizing any case histories of which they have knowledge.

References: (1) Kuesel, T. R. – "Earthquake Design Criteria for Subways", Structural Division Journal, American Society of Civil Engineers, June 1969.

(2) Parsons Brinckerhoff-Tudor-Bechtel – "Design Criteria for San Francisco Bay Area Rapid Transit System, Section 18, Aerial Structures", August 1965.

(3) Kruse, G. H. – "Rock Properties and Steel Tunnel Liners", Power Division Journal, American Society of Civil Engineers, June 1970.

(4) "Thin Double-Curvature Arch Dam Ranks as Middle East's Highest", Engineering News Record, April 4, 1963.

SUMMARY

In designing structures to resist earthquakes, the concept of a design criterion of controlled strains is proposed. For buried structures, the structure deformation must be the same as the ground deformation, and sufficient ductility to conform to this deformation is required. For aboveground structures, the strain or amplitude of vibration may be controlled by limiting the structure's natural frequency or stiffness.

For buried penstocks, the strain of the steel liner is limited by the confinement of the surrounding rock. Pre-compressing the liner may counteract tensile strains produced by working loads.

RESUME

Pour le dimensionnement de structures devant résister aux tremblements de terre on présente le concept d'un critère de dimensionnement basé sur les déformations contrôlées. Pour les structures enterrées la déformation de la structure doit être la même que celle du sol, et une certaine déformabilité est nécessaire pour permettre cette déformation. Pour les structures en surface, la déformation ou l'amplitude des vibrations peuvent être contrôlées en limitant la fréquence propre de la structure ou la rigidité.

Pour les vannes enterrées, l'élongation du manchon en acier est limitée par la roche environnante. En utilisant un manchon précontraint on peut diminuer les élongations produites par les charges actives.

ZUSAMMENFASSUNG

Zur Bemessung erdbebensicherer Tragwerke wird der Begriff eines Bemessungskriteriums, gestützt auf kontrollierte Dehnungen, vorgeschlagen. Für unterirdische Bauwerke müssen die Deformationen gleich denen des Bodens und eine genügende Duktilität für diese Deformationen vorhanden sein. Für oberirdische Bauten lässt sich die Dehnung oder die Schwingungsamplitude kontrollieren, indem die Eigenfrequenz des Bauwerkes oder seine Steifigkeit in gewissen Grenzen gehalten wird.

Für unterirdische Turbineneinläufe ist die Dehnung der Stahl-Auskleidung infolge der Einengung durch den umgebenden Fels begrenzt. Die Vorspannung der Auskleidung kann den durch die Gebrauchslast hervorgerufenen Zugdehnungen entgegenwirken.