Effect of Lining Stiffness on Tunnel Loading

Influence de la Rigidité des Revêtements sur le Chargement des Tunnels

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Summary

Load measurements on the tunnels at Garrison Dam plus the few observations available from other tunnels are utilized to demonstrate the advantages of relatively flexible tunnel lining.

Sommaire

Les mesures de charge sur les tunnels au barrage de Garrison et aussi les quelques observations qui ont été faites sur d'autres tunnels sont employées pour démontrer les avantages de revêtement relativement flexible pour tunnels.

Introduction

It has long been realized that load is attracted to stiff points and thrown off by yielding points. That this basic concept applies to loads on underground structures is indicated by observations on tunnels reported by TERZAGHI (1943), HOUSEL (1943) and SKEMPTON (1953), and by observations on culverts reported by CAIN *et al.* (1929) and MARSTON and ANDERSON (1913). The important factor is the relative stiffness of the tunnel lining compared with the adjacent ground; and further evidence that this is a dominant factor has been added by observations during 1948–54 on the tunnels at Garrison Dam (Garrison District, Corps of Engineers, 1949 and 1953). This is one of the world's three largest earth dams, and is approaching completion by the Corps of Engineers in North Dakota—the over-all project having been well described by SEYBOLD (1949).

Description of Tunnels

At this large multi-purpose project the outlet works include 8 tunnels, each about 1200 ft. long. Tunnels 1 to 5 are power tunnels with a 35 ft. bore diameter and a 3 ft. concrete lining; while regulating tunnels 6, 7 and 8 have slightly smaller diameters and lining thicknesses. Fig. 1 is a profile through one of the power tunnels. All tunnels are circular with a temporary support of steel ribs, and a permanent lining of reinforced concrete. For over-all economy, particularly in the large intake and surge tank structures at the portals, the tunnels are spaced relatively close—the clear distance between tunnels being about one bore diameter as shown by Fig. 2.

The tunnels were mined through the Ft. Union formation of early Tertiary age which is a clay-shale with beds of lignite coal. It may be perhaps better visualized as a highly compacted hard clay since it is susceptible to testing and analysis by the methods of soil mechanics as described by SMITH and REDLINGER (1953), and since it contributed a significant movement problem as reported by LANE (1955). The material is not cemented, but has considerable strength due mainly to heavy pre-consolidation under a load of about 100 ton/sq. ft. from sediments since removed by erosion.

Test tunnel—As there was practically no experience in tunnelling in the Ft. Union, a full-size 240 ft. long portion of tunnel 4 was built in an advance contract, and arranged to serve as a test tunnel—see Fig. 2. The general procedure utilized the steel ribs as elastic rings for measuring the loading. Stress in the steel was determined by Whittemore strain gauges, and diameter changes by a dial extensometer attached to the end of Lo-var tape.

The various measuring sections covered a wide range of relative stiffness. The rib sections (sections 4A and 4C in the

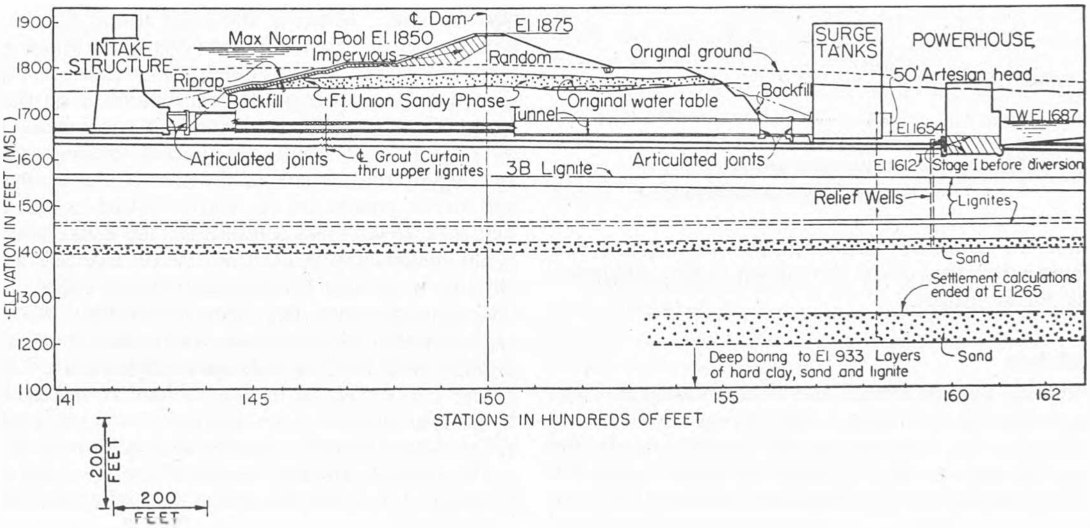

Fig. 1 Geological profile; outlet works
Profil géologique; les ouvrages de vidange

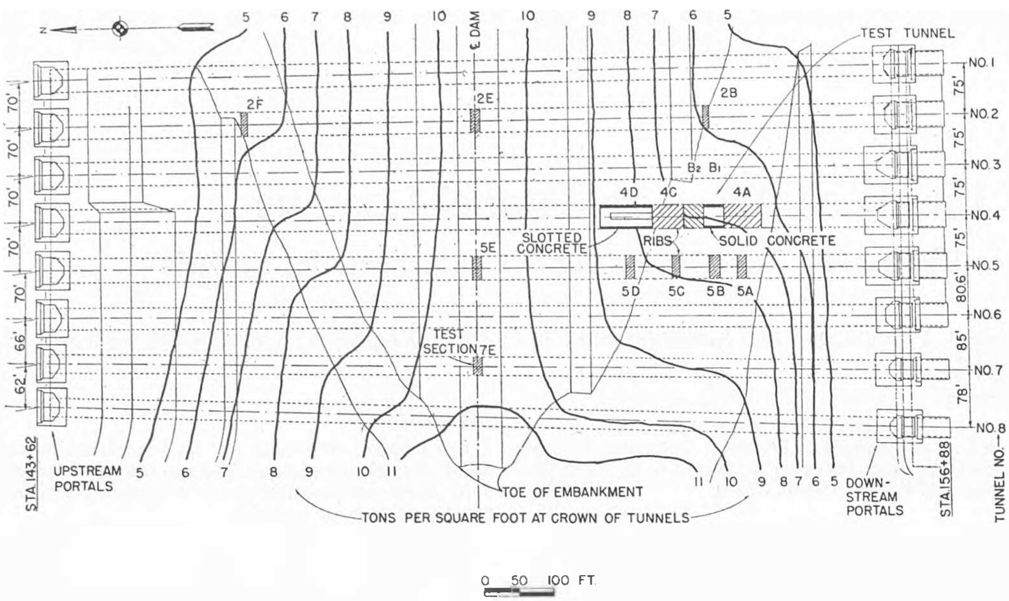

Fig. 2 Total overburden load
Pression totale de surcharge

test tunnel, and others in several of the main tunnels) were quite flexible with a stiffness of 10 to 15 per cent that of the ground. Section 4D was built as a slotted concrete section with heavy steel beams spanning the slots as shown by Fig. 3, and was about $3\frac{1}{2}$ times stiffer than the ground. By measuring the stress in the beams across each slot, this section served as a full scale weighing device for both the vertical and horizontal arch reactions. The maximum stiffness was represented by the full circle concrete lining of the prototype tunnels, and was somewhat greater than that of the slotted test section where the slots acted as partial hinges.

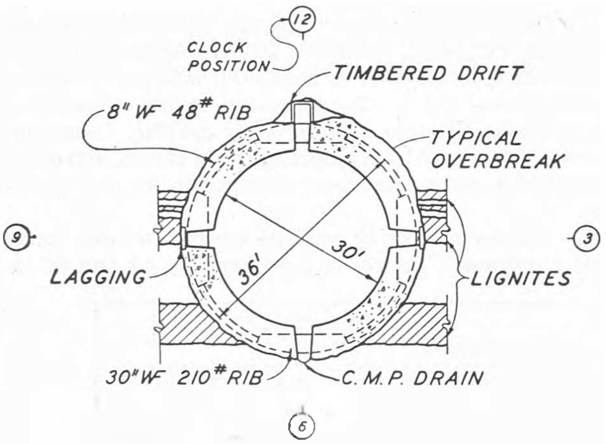

Fig. 3 Slotted concrete section
Section en béton avec des fentes

Loading Conditions

After completing the test tunnel, the dam embankment was placed in the tunnel area to avoid a load change after starting the main tunnels. In constructing the main tunnels the general procedure was to mine a tunnel full length using full face excavation with steel ribs for temporary support, and then to concrete this tunnel before allowing any mining in either of the two adjacent tunnels. Fig. 4 shows the order of construction which resulted in three main loading conditions. The single tunnel case represented a tunnel mined and supported by ribs alone. The surface loading case was caused by addition of the embankment load, and applied only to the test tunnel. The multiple tunnel case represented the effect of adjacent mining where the load arched over the tunnel being mined to increase the load on the previously constructed adjacent tunnel.

Observed loading—In all cases the vertical diameter decreased and the horizontal increased by about the same amount. This showed the vertical load as the activating load, forcing down the crown and forcing out the spring-lines, there to build up the passive load. Diameter changes in rib sections of the test tunnel were about 1 in. in the single tunnel case, plus another in. from adding the embankment load and from adjacent mining; or a total of about 2 in. In the stiffer slotted test section, the diameter changes after concreting were much less—about $\frac{1}{4}$ in. from the embankment load, and $\frac{1}{8}$ in. from mining each adjacent tunnel; or a total of around $\frac{1}{2}$ in.

The vertical load on the ribs of the temporary support in the single tunnel case ranged from 10 to 15 per cent of the overburden load. Most of the load added by the embankment arched over the flexible rib sections to the stiffer ground at each side. In contrast, this added load was attracted to the stiffer slotted concrete section 4D—the increase on the tunnel being about 150 per cent of the increase in overburden load as shown by Fig. 5. The effect of adjacent mining caused a further increase in load—small in the case of the flexible rib sections, and much greater on the stiffer slotted concrete section 4D. Temperature changes complicated the load change when tunnel 5 was mined, and the dotted line on Fig. 5 is an approximate attempt to correct for the temperature effect. At the end of the measurements the concrete section 4D was carrying approximately 100 per cent overburden, while the flexible rib sections were carrying only about 20 per cent. Throughout the measuring period, the horizontal load H and the vertical load V were approximately equal in the rib sections, while in the much stiffer slotted concrete section, H was about $\frac{1}{2}V$.

The effect of stiffness was equally pronounced on the bending moment—the stiffer the lining the higher was the moment, as shown by Fig. 6. In both the rib and slotted concrete sections the contribution of moment to total stress was nearly three times

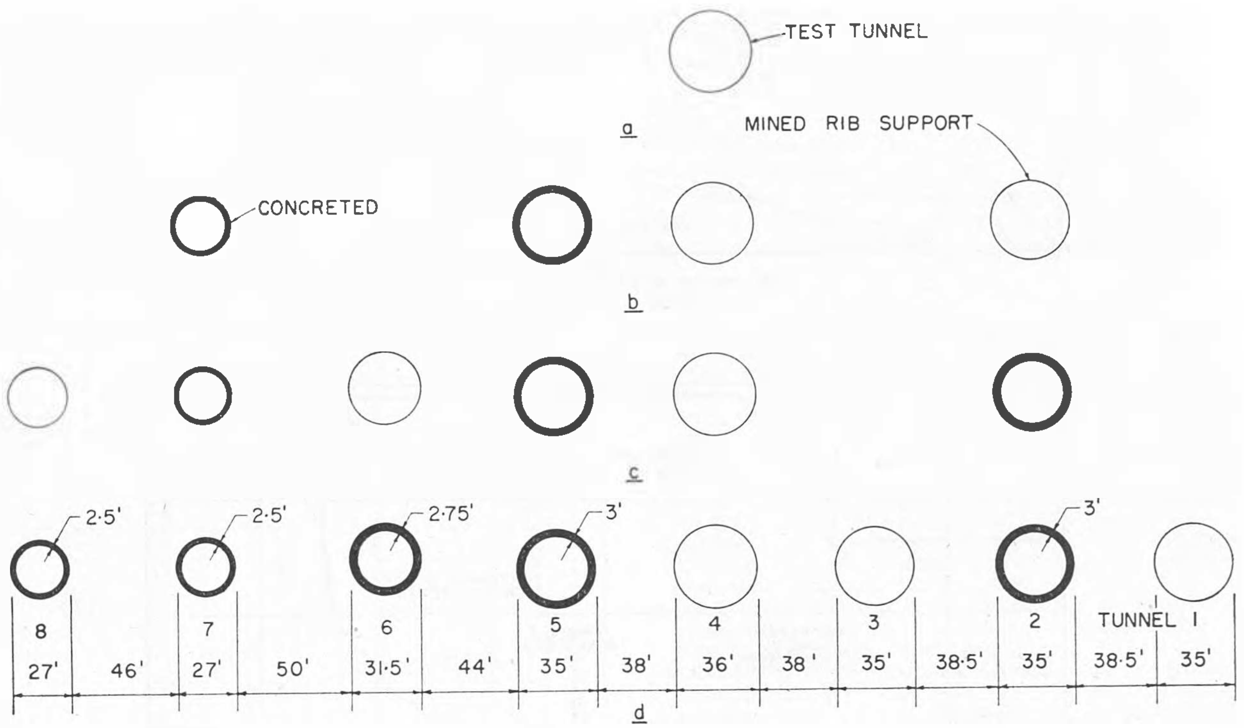

Fig. 4 Order of construction opposite test tunnel
Succession des opérations au voisinage du tunnel d'essai

the contribution of thrust. To compensate for the effect of temperature change on the moments, thrusts, and deflections, a type of difference function plot was found useful such as Fig. 7. In the sign convention used, the vertical diameter change D_y is negative, also the springline moment M_s, so the difference functions represent twice the average diameter change and moment at the 4 clock positions shown in Fig. 3. That the curves of Fig. 7 could be matched by adjusting the scales shows that the 3 difference functions were linearly related.

Such relationship is compatible with theoretical ring equations, all of which take the form

$$M = CpR^2 \qquad \ldots . (1)$$

where p is the unit load, and R the ring radius.

Whence

$$\frac{(M_c - M_s)}{(C_1 + C_2)R^2} = (V - H) \qquad \ldots . (2)$$

where M_c is the crown and invert moment, M_s the springline moment, and the constants C_1 and C_2 depend upon the shape of the load distribution diagram. Equation 2 is perfectly linear where V and H have the same type of distribution, which appears to have been the case for the Garrison Tunnels as shown by Fig. 7.

Ring action—These observations show that the stiffer the lining, the larger the load and moment and the greater the load difference $(V - H)$. Similar conclusions are indicated although more from a qualitative standpoint, by the results of the few other investigations of tunnel loads; as, for example, the data on Chicago tunnels reported by TERZAGHI (1943). From this evidence it appears that a circular tunnel ring can be visualized as carrying its activating load V as one increment of V which is balanced by the horizontal load H and as a second increment which is supplied by the bending resistance of the ring B_R. This is illustrated by writing equation 2 in the form

$$V = H + F(M) \qquad \ldots . (3)$$

where the moment function may approach B_R.

If the ring is very flexible with only negligible bending resistance it readily deforms, creating a high passive horizontal load; or as a limiting case

$$H = V \quad \text{and since } V - H = 0 \quad M = 0 = B_R$$

If the ring is very stiff, B_R is high; the deformation is small; H is small, so $(V - H)$ is large; and M is high. As a limiting case with H negligible

$$H = 0 \quad V - H = V \quad M = B_R$$

Hence, with some over-simplification, this concept can be represented by writing equation 3 in the form

$$V = H + F(B_R) \qquad \ldots . (4)$$

This shows the automatic safety inherent in a circular ring which is capable of adjusting itself to carry the activating load V by a combination of bending resistance and of deforming to build up the passive load H. Should the combined stress reach the yield point, B_R may be reduced; but this is offset by an increase in H as it is built up by the greater deformation of the now more flexible ring. As long as the ring maintains its integrity it is thus capable of self adjustment to carry its load by a combination of stresses and deformations which probably follow the principles of least work.

Conclusions

The foregoing evidence shows the two pronounced effects of lining stiffness which can be expected under reasonably similar conditions where the formation is sufficiently competent to preserve the ground arch.

(1) A tunnel lining relatively stiffer than the ground attracts load, while one which is more flexible sheds load. Similar behaviour has been reported in room and pillar mining where a series of equal-sized pillars were successful; but when one much larger pillar was injected in the pattern it failed since its greater stiffness attracted far more than its share of the load.

(2) A structurally stiff lining carries a high percentage of its loading by bending moment, while a flexible lining more fully

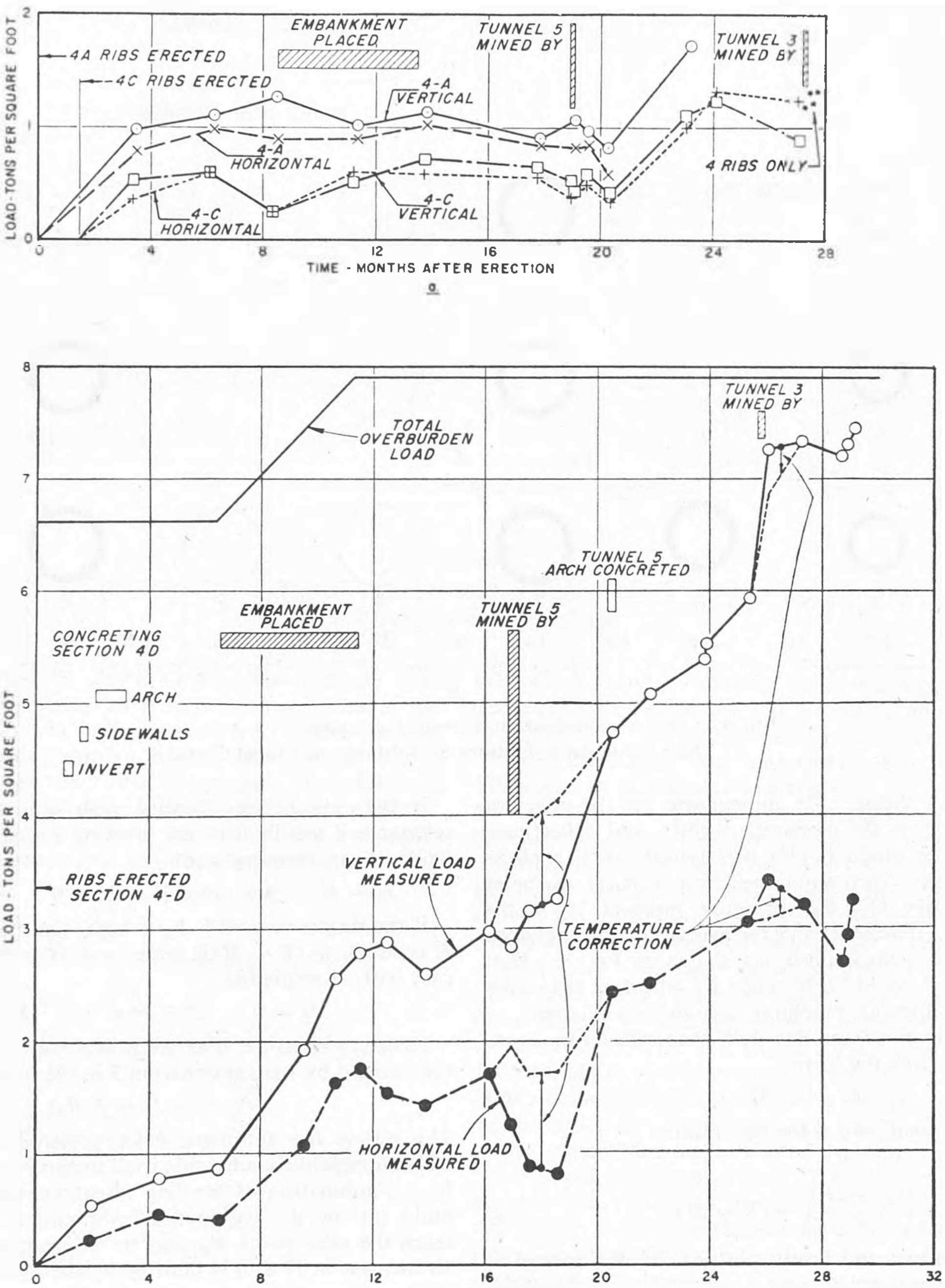

Fig. 5 Measured loads—slotted concrete section 4D
Charges mesurées — section en béton fendue 4D

utilizes the resistance created by developing a substantial passive or horizontal load.

These are not new concepts, but it is frequently helpful to review basic premises in the light of additional field evidence. Their wider application for the single tunnel case in reasonably competent ground should result in economy by using more flexible tunnel linings with increased reliance on the ground to carry a major share of the load. One approach is the increased use of flexible metal culverts to reduce the load received from high fills. Another approach in the stiff London clay has been reported by GROVES (1943), using pre-cast concrete segments for tunnel lining with a sheet of compressible material in each joint to introduce some flexibility while preserving high resistance to thrust. An interesting variation is the injection of a pre-stress into a concrete block lining to resist internal water pressure in the London experiments described by TATTERSALL *et al.* (1955).

For a less competent formation, as a soft clay, there is still likely to be considerable arching to reduce the load on the flexible temporary support; but with time the shear stresses then set up are apt to dissipate and destroy the ground arch as indicated from results on Detroit, Chicago and New York tunnels reported by HOUSEL (1943), TERZAGHI (1942) and RAPP and BAKER (1937). Hence, the present state of knowledge makes it prudent to design a permanent lining in soft clay for essentially full overburden.

The problem is more complicated for the multiple tunnel case where an array of closely spaced tunnels is likely to carry 100 per cent of the overburden load. In addition, those tunnels mined first may experience severe loading from adjacent mining

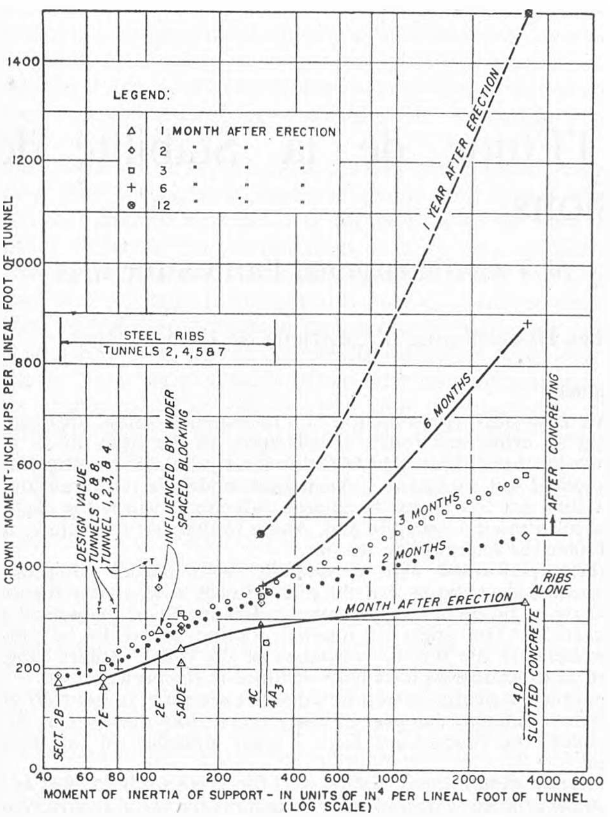

Fig. 6 Crown moment *versus* stiffness of support
Moment à la clé en fonction de la rigidité

as was the case at Garrison, and may be the explanation of the results in London reported by SKEMPTON (1953).

While reinforced concrete has several advantages including durability, proportioning to carry such a high thrust inevitably leads to a stiff concrete section with the accompanying disadvantage of carrying much of the load by its bending resistance. For the special case of penstock tunnels there are theoretical advantages to a concrete encasement designed to act integrally with the steel liner. However, much still has to be learned of the interaction between steel and concrete, so there is a fertile field for development of durable tunnel linings able to carry high thrust while preserving considerable flexibility.

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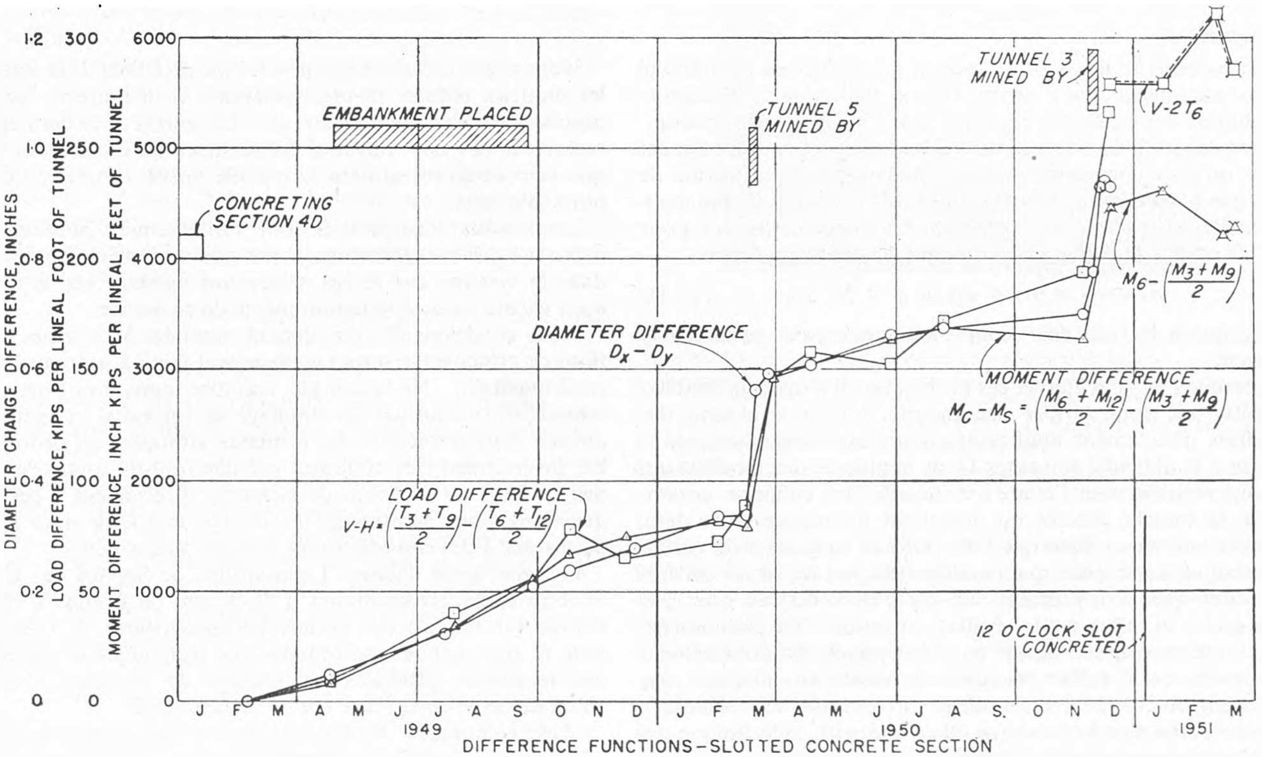

Fig. 7 Difference functions—slotted concrete section
Fonctions de différence — section fendue en béton