HORIZONTAL EARTH PRESSURES ON BOX CULVERTS, ABUTMENTS AND WALLS DUE TO WHEEL LOADS

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SUMMARY

This paper presents a more fundamental understanding of the nature of live load induced horizontal earth pressure and its interaction with earth pressures due to fill and compaction. 'Live load surcharge' horizontal (or lateral) earth pressure is shown to be the cumulative and residual resultant of the previous loading history, including loading during construction. Consequently, live load induced horizontal earth pressure can exist without concurrent loading by traffic wheel loads. This is in marked contrast to the traditional treatment of 'live load' in structural design codes. This new concept has considerable implications for the design and construction of box culverts, abutments and retaining walls. Design expressions are given for the horizontal pressure due to the AUSTROADS T44 Truck Loading and the Heavy Load Platforms.

KEYWORDS

Box culverts, Wheel loads, Abutments, Walls, Horizontal earth pressure, Live load surcharge, Lateral earth pressures, Compaction pressures, Residual pressures.

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INTRODUCTION

The nature of roadway traffic induced earth pressures acting on structures and culverts is complex and many bridge design codes, including the AUSTROADS (1989 draft) code, give rules regarding this area. In particular, vertical live load pressure is modelled by using a pyramid type dispersal of wheel loads. In contrast, horizontal live load earth pressure is modelled by using a 'live load surcharge' equated to a height of fill (see Fig.1,2).

![Fig.1 Dispersal of concentrated loads to structure](image1.png)

![Fig.2 Live load surcharge for a box culvert](image2.png)

The disparity of treatment is most obvious for box culverts where the lack of a logical connection between the two raises questions of interpretation and application of the code rules. This paper presents a new concept giving a more fundamental understanding of the relationship between wheel loads and 'live load surcharge'. To introduce this concept we will first examine the horizontal pressures caused by compaction.

COMPACATION PRESSURES

It is known that soil confined against a retaining structure will exert an increased horizontal pressure on the structure during compaction. Broms (1971) presented an understanding of the development of horizontal earth pressures during compaction. The following is based on this understanding.
The state of stress for a non-cohesive soil confined against a rigid and unyielding structure during compaction can be simulated in a triaxial test where the confining pressure is adjusted to prevent lateral deformation during the vertical pressure change. An actual stress diagram is shown in Fig.3, and an idealized approximation in Fig.4.

With reference to Fig.3, the loading line OA follows the Ko line with a near linear increase in horizontal pressure. When the vertical pressure is reduced from its maximum of Pmax at A, it is found that there is very little reduction in horizontal pressure OH until some point B. Horizontal pressure then reduces non-linearly to D and then follows a near linear reduction along the K'o line. If unloading from A were to be stopped at F and then the vertical pressure increased again,
it would be found that the reloading curve from F will be as shown dashed i.e. there will be little horizontal pressure increase until the Ko line is reached again near A.

In Fig.4, let Pc represent the minimum overburden pressure at which the horizontal pressure OH can be maintained under the passage of a compaction vertical pressure Pmax. We can express Pc in terms of a critical soil depth Zc and soil density i.e. Pc = Zcγ

Then, from OH = EA

\[ K'o.Pc = K'o.γ.Zc = Ko.Pmax \]  
(1)

or

\[ Zc = \frac{Ko.Pmax}{K'o.γ} \]  
(2)

Broms derived this relationship and stated that it could be used to calculate residual horizontal pressure once the maximum vertical compaction pressure Pmax that occurs at the point is known. He went on to say that, at least for dense sands, the Boussinesq stress equations give values that correspond closely to measured vertical pressures under concentrated loads.

Broms also presents references to show that measured values indicate that the earth pressure coefficient Ko can be estimated, by the relationship Ko = (1 - Sinθ), where θ is the angle of internal friction.

Ingold (1979) builds on the work by Broms but uses the active earth pressure coefficient Ka for Ko (Ka being considered as an appropriate value for a yielding structure) and the passive earth pressure coefficient Kp for K'o. He uses the Boussinesq equation for maximum vertical pressure under a line roller to define Pmax.

i.e. \[ Pmax = \frac{2.P}{\pi.Z} \]  
(3)

where: P = roller line load per unit length
Z = depth directly under the line load.

Substituting Ko = Ka, Pmax as given by equation (3) and K'o = Kp = 1/Ka into equation (2), for Z = Zc, we have:-

\[ Zc = Ka.\sqrt{\frac{2.P}{\pi.γ}} \]  
(4)

To calculate the maximum residual horizontal pressure, refer to OH in Fig.4 and substitute Ko' = 1/Ka and Zc from (4) into equation (1) as follows:-

\[ OH = K'o.γ.Zc = \sqrt{\frac{2.P.γ}{η}} \]  
(5)
where $OH = \text{maximum residual horizontal earth pressure due to compaction}$ and occurs under the line roller at depth $Z_c$. Refer also to Figures 5, 6, 7 for illustration of derivation of an idealized compaction horizontal pressure diagram for a culvert side by one pass of a compaction roller.

![Diagram showing maximum (peak) vertical pressures under one pass of roller.](image)

Fig. 5 Showing maximum (peak) vertical pressures under one pass of roller.

![Diagram showing stress diagram for points 1, 2, 3.](image)

Fig. 6 Showing stress diagram for points 1, 2, 3.

![Diagram showing residual compaction pressure.](image)

Fig. 7 Showing compaction pressure.

In these figures 1E, 2E, 3E refer to the state existing before roller passage and 1F, 2F, 3F to final after roller has passed. For real soil behaviour there would be some rounding near point $C$ in Fig. 7 (refer to unloading curve between $B$ and $D$ in Fig. 3). It is to be noted that the maximum vertical pressure occurring at any point at or below the critical depth $Z_c$ (shown as point 2) during the loading process is multiplied by the $K_o$ coefficient to calculate the residual horizontal pressure at that point, and that subsequent loading will not change the residual horizontal earth pressure unless the new maximum vertical pressure exceeds the previous maximum vertical pressure at the point concerned.
The pressure profile developed during compaction of successive layers is illustrated in Fig. 8, leading to a simplified horizontal pressure diagram due to compaction shown in Fig. 9. Some rounding is shown dashed near point 'C', as explained previously.

![Diagram showing pressure profile and horizontal pressure due to compaction.](image)

**Fig. 8** Showing horizontal pressure due to compaction of successive layers.

![Diagram showing simplified horizontal pressure diagram.](image)

**Fig. 9** Showing simplified horizontal pressure diagram due to compaction.

Experimental work at the TRRL, including full scale compaction testing has been reported by Carder et. al. (1977, 1980) and by Symons and Murray (1988). This work has confirmed the development of residual horizontal pressures due to compaction for sands, silty clays and clays and supports the use of the coefficient of earth pressure at rest, Ko rather than Ka. The work at the TRRL also shows that residual horizontal pressures due to compaction can be considered to:

(a) remain as permanent pressures for sands,

(b) dissipate or reduce with time to the Ko (earth pressure at rest) value for silty clays and clays.
Carder et al. (1980) and Symons and Murray (1988) have reported that four months after construction using silty clay, the compaction pressures had reduced and lay close to the Ko line. The reduction for heavy clay was about 12% over a four week period.

This dissipation and reduction of compaction pressures for cohesive materials, and lack of dissipation for granular non-cohesive materials has important ramifications for design when considering combinations of earth pressures, including live load induced horizontal earth pressures.

Prior to dealing with horizontal earth pressures due to wheel loads, it is relevant to consider vertical pressures under wheel loads.

VERTICAL PRESSURES UNDER WHEEL LOADS

The pyramid type distribution is clearly a simplification which does not predict the maximum vertical pressure, nor its distribution under a wheel load.

Work done between about 1920-1950, as reported by Spangler and Ustrud (1940), Spangler and Hennessy (1946), Spangler and Mickle (1956), Tschebotarioff (1951) and Spangler and Handy (1984) indicates that the bell shaped vertical pressure distribution under concentrated wheel loads can be closely approximated by the use of Boussinesq equations, notwithstanding that soil is known to depart from the ideal elastic medium strictly required for the equations.

Tschebotarioff (1951) discusses results of tests on sands in the 1920's which indicate that vertical loads are more concentrated than calculated by Boussinesq equations. Pressure distribution changes could well be caused by the departure from the assumed ideal infinite elastic half space that occurs when we place a retaining wall or a buried culvert in such a space, and by soil structure deformations and interaction. The friction on the surfaces of the culvert or wall could likewise change the earth pressures. It is thus possible that localised stresses are higher than predicted by Boussinesq equations. On the other hand the presence of road pavement would clearly reduce peak pressures under wheel loads. Considering these factors and the variability inherent in soils it would appear to be sufficiently accurate for a general case to adopt the circular area Boussinesq equation to calculate Pmax as the maximum vertical pressure directly under a wheel load. This approach has the advantage of starting with a finite surface contact pressure, which as an approximation, could be taken to be the tyre pressure of a wheel. It would also seem desirable to use the same wheel loads and wheel spacing as used in the design vehicle i.e. 48kN wheels of the AUSTROADS T44 design vehicle. A contact pressure of 600 KPa is implied by the contact area of 400X200 mm given in the code.
LIVE LOAD INDUCED HORIZONTAL EARTH PRESSURE

The horizontal pressures induced by wheel loads are considered to be formed by the same process as those due to compaction. Individual wheel loads would induce a 'Boussinesq type bulge' of horizontal pressure under each wheel as illustrated in Fig. 10.

Similarly, a different shaped "bulge" would be developed for loading by a fixed pattern of multiple wheels, eg. tandem axles, abnormal vehicle, etc.

Under passage and transverse tracking of one wheel, the individual pressure "bulges" will combine to form a horizontal pressure profile that could be represented by the envelope of maximum pressure under a single wheel. A different pressure profile would be appropriate for the T44 tandem axles considered as a fixed pattern load of four 48 kN wheel on two 1.8m axles at 1.2m centres. The T44 tandem axle pressure profile values can be closely approximated for design purposes by an expression based on a strip type loading, ie.

$$ (T44 \text{ tandem strip}) = Ko \left( \frac{35}{H + 0.2} - 4 \right) $$

Fig. 11 shows horizontal pressure profiles for the T44 tandem axle and its strip approximation as well as profiles for the AUSTROADS (1989 draft) heavy load HLP320 and HLP440 platforms.
The heavy load platforms can be closely approximated by adding a 4 kPa horizontal pressure to the strip (T44 tandem) expression, ie.

\[(HLP \text{ strip}) = (T44 \text{ tandem strip}) + 4 \]  

(HLP strip) = (T44 tandem strip) + 4 \hspace{1cm} (7)

Horizontal pressure (kPa)

0 \hspace{1cm} 5.0 \hspace{1cm} 10.0 \hspace{1cm} 15.0 \hspace{1cm} 20.0 \hspace{1cm} 25.0 \hspace{1cm} 30.0 \hspace{1cm} 35.0 \hspace{1cm} 40.0

Horizontal pressure plotted for wheel loads with no impact allowance. (pressure due to fill not included)

600 kPa wheel contact pressure

Soil density = 20 kN/m$^3$

$k_0 = 0.5, \hspace{0.5cm} k'_0 = 2.0$

**Fig.11 Horizontal pressure profiles**

**COMBINATION OF LIVE LOAD AND COMPACTION PRESSURE**

Based on the explanation given here, it can be seen that horizontal earth pressures from compaction and traffic wheel loads are not additive, but need to be superimposed to determine the maximum horizontal earth pressure at any point. For clays, both compaction and live load induced pressure may dissipate and reduce to the Ko value with time. However, this is not the case for sands.

Following the reasoning given above, it is considered that live load induced horizontal earth pressure is the residual resultant of the previous loading history. Consequently, at any time after the initial individual wheel loading, live load induced residual horizontal earth pressure can exist without concurrent loading by traffic wheel loads.

This concept is in marked contrast to the traditional treatment of live load in structural analysis and bridge design codes.
FIELD TESTING AND MEASUREMENT OF HORIZONTAL EARTH PRESSURES

Few reports have been published on field testing of culverts or walls, and those that have, appear to have assumed that the horizontal effects for separate wheel loading positions are independent. The superposition of compaction pressures and horizontal pressures due to wheel loads likewise have generally not been specifically allowed for.

Perhaps the first evidence to support the concept presented by the author is reported by Spangler and Mickle (1956) on p9 in regards to measuring horizontal pressures on a wall in 1931:

The first surcharge load caused relatively large outward movements, both rotation and translation, but subsequent loadings did not produce any movement of consequence. Also, when the experimental wall was again loaded during the current series of loadings, the wall movements were practically negligible. Apparently the first surcharge caused the wall to reach a state of equilibrium and no further movements occurred.

and again on p15 in regards to tests in 1951:

In those cases where more than one surcharge was placed on the same backfill, the pressure on the wall due to backfill alone was frequently greater after removal of a surcharge than it was prior to loading. In other words, there were residual pressures against the wall after removal of the first surcharge.

These comments are of particular relevance because the fill in all of these tests was 'hand shoveled up to the wall' and not compacted in any way. Thus compaction pressures were not a complicating factor, as in the case for more recent field tests.

CULWAY

Further circumstantial evidence supporting the concept of residual horizontal pressures appears to exist via the Culway System currently in use at many sites in Australia.

Culway weighs an axle of a vehicle as it crosses a culvert top by measuring the bending strain at the underside of the top slab of the culvert, which is generally integral with the culvert side walls and accordingly is a fixed ended member. The fixing moment is a function of the soil pressure distribution on the culvert legs. The consistency of reading of various axle loads over a wide axle load range implies that the fixity is near constant and this can only be so if the soil pressure profile on the legs is not significantly changed by the passage of an individual wheel load, i.e. residual horizontal earth pressures predominate and any wheel load less than the previous maximum (due to compaction or wheel loads)
at the location would have no effect on the residual soil pressure profile on the legs.


The N.A.A.S.R.A. (1976) code requires a 1.2m live load surcharge. This is compared with the T44 tandem strip approximation presented in this paper as equation (6).

Culvert comparison (see Fig. 12) is for a culvert leg pinned at the bottom and fixed at the top.

![Diagram](image)

**Fig. 12 Moment ratio \( M_R = \frac{\text{T44 moment}}{1.2\text{m surcharge moment}} \)**

It can be seen from Fig. 12 that the top corner moments in culverts reduce considerably for the T44 tandem strip for fills over culvert exceeding about 500mm, i.e. for most practical situations of culvert use.

Refer to Fig. 13 for the T44 tandem strip and the HLP strip 'equivalent surcharge' for moment and shear for a rigid wall or abutment about its base. The live load surcharge required by AUSTROADS (1989 draft) is shown for comparison.

No simple comparison is possible for abutments and walls because there are different 'equivalent surcharges' for moment and shear about the abutment/wall base. It would appear that the 1.2m surcharge is too high for fills exceeding about 2m, whereas the AUSTROADS proposed variable surcharge values are generally too low, particularly for fills exceeding about 5m.
It is suggested that the T44 tandem strip approximation for the T44 vehicle and the HLP strip approximation for the heavy load platforms are appropriate for design purposes. These, together with the concept presented in this paper, allows for rational combination of wheel load induced horizontal pressures with other pressures at serviceability and ultimate limit states, which is not the case for current codes, and the AUSTROADS draft.

CONCLUSIONS

This paper presents a more fundamental understanding of the nature of live load induced horizontal earth pressure and its interaction with earth pressures due to fill and compaction. 'Live load surcharge' horizontal (or lateral) earth pressure is shown to be the cumulative and residual resultant of the previous loading history, including loading during construction. Consequently, live load induced horizontal earth pressure can exist without concurrent loading by traffic wheel loads. This is in marked contrast to the traditional treatment of 'live load' in structural design codes. This new concept has considerable implications for the design and construction of box culverts, abutments and retaining walls. Design expressions are given for the horizontal pressures due to the AUSTROADS T44 Truck Loading and the Heavy Load Platforms.
REFERENCES


