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The consideration of live loading in the design and assessment of earth structures

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ABSTRACT: The live load component for the design of earth structures has historically been adopted from bridge engineering. Of those live loads considered by bridge engineers only traffic load is of relevance to earth structures design. For bridge design the traffic load is in direct contact with the bridge deck structure and the application of load as quasi-static is actually modelling cyclic loading over the design life of the structure.

The application of similar loads on earth structures as quasi-static loads invokes a model of a constant load applied through the earthwork as a bulb of applied pressure to depth or as an additional load over the full depth of an earth retaining structure when modelled using limit equilibrium techniques.

An approach developed using EN1990 (BSI, 2002 & 2009) for the design of bridge foundations and earthworks on the A!4 Cambridge to Huntingdon Improvement scheme in the UK took account of the potential overdesign applied by the live load particularly when it is considered that partial factors are required by EN1997-1 (BSI, 2004 & 2009) for geotechnical design.

The design, construction and testing of a 45-kilometre haul road for heavy module transport in Kazakhstan indicated that the increased load experienced by the ground during traffic movements was significantly lower than would have been expected analytically.

This paper develops both approaches to suggest a more pragmatic approach for the consideration of live traffic loading for the design of both new and remedial earth structures over their design life,

KEYWORDS: Earthworks, Loading, Design

1 INTRODUCTION

The design of Earthworks and Earth Structures involves the determination of forces from both dead loads, predominantly the ground but also consideration of transient live traffic loads predominantly traffic loading. The determination of live traffic loads in earthworks has been taken from the approach used by structures engineers in the design of bridge decks and retaining walls.

Design traffic loads on a National basis and for highway loading varies from 10kN/m^2 to 52kN/m^2 in Europe (CEN, 2021), is 12kN/m^2 in the USA (AASHTO, 2020) and 10kN/m^2 in Morocco. These loads, however, reflect those used by bridge engineers rather than for the design of earthworks.

This paper considers how theses design loads can be rationalised.

2 MODELLING OF APPLIED LOADS.

2.1 *Structural derivation of loading*

As part of the design process for the A14 Cambridge to Huntingdon Improvement scheme in the UK the derivation of live loads for use in the design of foundations for highways structures was examined. Live loads are applied in structural design to prevent Ultimate Limit State (ULS) failure of the structure defined as that which would result in loss of service. By its nature this approach considers 'factored' live load effects in combination even though the likelihood of occurrence is extremely small.

Historically, for highway structures designed in the UK these variable actions would have been presented as part of a combination of dead and live loads or split into the two components that were typically 'unfactored' when they were presented to the geotechnical engineer.

The introduction of Eurocodes, particularly EN 1991 require that individual live loads are determined for each component of the of the variable load. This allows individual live load components to be considered, and a suitable partial safety factor applied. This would normally be in excess of 1.0 hence further increasing the design live load.

In the UK, for Design Approach 1, Load Combination 2 of EN 1997-1, that is critical for slope stability analysis a partial factor of 1.35 would be applied to a normal live traffic load of 20kN/m^2 resulting in a design value of 27kN/m^2. If a maximum direct analogy of the live load applied to bridge design was adopted then the load of 37.5kN/m^2, for a Special Vehicle (BSI 2003 & 2007), would result in an increase to 48.75kN/m^2 by application of the appropriate partial safety factor.

2.2 *Proposed approach to foundation and earthworks design*

The approach to live loading on the A14 project (Nowak, Patel & Sandberg, 2021) considered that the established approach to live traffic loading represented the once in a lifetime occurrence, as shown in Figure 1, and did not recognise that additional safety factors were applied to the design of foundations and earthworks so making the design loads considered greater would be experienced by the foundations.

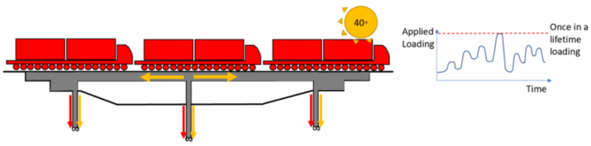

Figure 1. Load combination considered by the structural designer.

The design loading in Figure 1 above is taken as the worst case for the design life and, hence, can be considered conservative.

In order to reduce the live load component to closer represent that experienced by a structure or earthwork over its design life the Serviceability Limit States (SLS) in EN 1990 were considered and the Frequent Case deemed the most appropriate. Adoption of this load case allowed Special Vehicle Loading to be ignored and a partial factor of 0.75 to applied to the 20kN/m^2 normal traffic loading resulting in a design live load of 15kN/m^2.

This approach was adopted by the Client, UK National Highways, not only for the design of bridge structure foundations but also for retaining wall and earthworks design.

The Client also incorporated the approach into their Knowledge Base website for use by others.

The Frequent Load case to EN 1990 is illustrated in Figure 2 below.

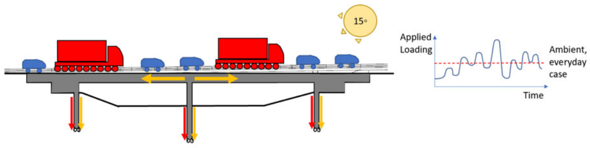

Figure 2. Optimised loading using Frequent Load Combination

2.3 *Application of load in geotechnical analysis*

When bridge engineers consider the application of live load, whether that be traffic wind or thermal, they are considering that the load applied is directly to the structure that they are designing. The loads applied are termed 'quasi-static' in order to convert what is a cyclic load over the design life of the structure into a simplified constant load that can be applied in the design of the structure.

The term 'quasi-static' has been adopted for these loads in earthworks and retaining wall design, but the term has a different interpretation in geotechnical engineering rather than the simplistic application at the surface of the earthwork or retaining wall to be designed.

If the impact of settlement due to live load acting on an earthwork were considered, analysis would be carried out using a Boussinesq distribution of applied pressure with depth. Considering a live traffic load as a strip load this will results in the soil below the footprint of the loaded area being subjected to additional load to a depth of some three times the width of the applied load. In the case of a dual 2-lane highway of some 7 metres width this would be a depth of some 21 metres.

When live load is applied behind a sheet pile or bored pile retaining wall in Limit Equilibrium analysis it will be applied over the full height/depth of the retaining structure multiplied by an earth pressure coefficient.

When live load is considered in slope stability analysis it acts over the full depth of slice which underlie or intersect the loaded area. This means that, as each slice is of different depth, the load will be applied to a greater or lesser height of soil than the adjacent analysed slice and that a constant applied pressure at depth is not being considered.

It is also questionable whether live traffic load should be applied to an earthwork when settlement of the underlying ground is being considered. UK BS6013 (BSI, 2009) considers that as the load is transient rather than a maintained 'quasi-static' load it should be ignored. A major project currently being designed and constructed in the UK is applying live load from traffic when overall embankment settlement is considered.

3 RESULTS OF FILED MONITORING OF TRAFFIC LOADING

3.1 *Introduction*

The 36-kilometre-long haul road for the Tengizchevroil Future Growth Project (FGP) was designed and constructed to facilitate the transport of 252no partially constructed modules from a purpose-built Ro-Ro terminal on the Caspian Sea to the construction area within the oilfield (Nowak & Barr, 2022, 2024).

A typical module is shown in Figure 3 below. Module and trailer weights for some modules were in excess of 60kN/m^2 when considered as a Uniformly Distributed Load (UDL) and 45% of the module transports were in excess of 40kN/m^2 UDL. This was a unique loading situation as the weight of the module transports were nearly always greater than the dead load imposed on the underlying ground from the embankment construction which was a maximum 1.5 metres high comprising locally won uniformly graded sand topped with an imported crushed rock capping layer.

Figure 3. Typical module transport of a pipe rack

The ground underlying the haul road compromised, in the upper 5 metres, recent Caspian Sea deposits of loose fine grained granular soils interlaced with channels infilled with normally consolidated cohesive soils.

3.2 *Haul road design.*

Both slope stability and bearing capacity calculations were initially undertaken with a target minimum factor of safety of 1.5 as allowed for by local codes. Subsequently, 2D PLAXIS analysis was undertaken to endeavour to establish the amount of cumulative settlement under cyclic loading from module transports. 3D PLAXIS Analysis may have been more appropriate but would not have significantly reduced settlement as load spread was confined by the modules being of similar width to the embankment crest

Design parameters for the PLAXIS analysis were as summarised in Table 1 below:

Table 1. PLAXIS input data.

Parameter	Unit	Soft Clay	Sand
Y_b	kN/m^3	18	18
$E_{oed\ ref}$	kN/m^2	2000	75000
$E_{50\ ref}$	kN/m^2	4000	75000
$E_{ur\ ref}$	kN/m^2	12000	225000
Φ'	deg	26	38
c'	kN/m^2	2	1
pref	kN/m^2	100	100
m	--	0.75	0.5
K_0	--	0.765	0.384

In analyses the load from the module transport was applied directly to the running surface of the haul road as a UDL to mirror a quasi-static load. The only subprogramme involving cyclic loading was examined but was found to be inappropriate as it was developed for cyclic loading of fine granular soils.

3.3 *Field monitoring*

The 2D PLAXIS analysis of both settlement and pore pressure increase in the normally consolidated cohesive soils was not fully conclusive and the project required a monitoring regime in order to provide an early warning of impending failure prior to the actual failure of the haul road led to a module toppling over during transport This was to be provided by real time monitoring of vibrating wire piezometers installed in the cohesive soils and topographic survey points installed in the running surface of the haul road at 50 metre intervals.

In order to further inform the monitoring regime a dynamic embankment trial was initiated comprising the passage of a 25m x 8m multi-wheeled trailer over a 2-kilometre section of the completed haul road. Load was applied to the trailer using crane counterweights and module passes of 3 x 20kN/m^2, 3 x 40kN/m^2, 7 x 70kN/m^2, 3 x 40kN/m^2 and 3 x 20kN/m^2 were carried out over a 12-day period.

The test trailer is shown in Figure 4.

Figure 4. Test trailer for the dynamic embankment trial

Prior to the dynamic embankment trial, the likely performance of the underlying ground under applied load was modelled in 2D PLAXIS and the results are presented in Figures 5 and 6 below.

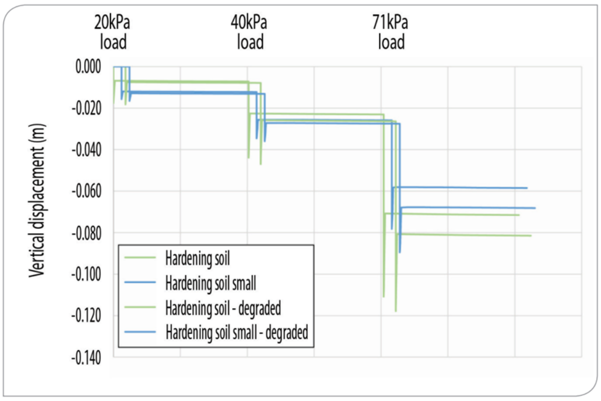

Figure 5. Vertical deformation predictions, centreline of haul road

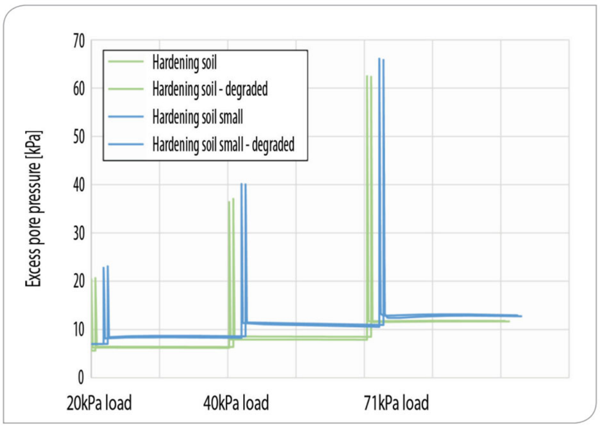

Figure 6. Elevated porewater pressure predictions at 2.5metres below ground level

The results compared well with those modelled earlier in the analysis programme and also with the results from a static embankment trial carried out to simulate loading and determine consolidation properties of the normally consolidated cohesive soils underlying the haul road. They also compared well with the work of Leroueil (1980) and Tavernas and Leroueil (1980).

Results from the dynamic embankment trial are presented in Figure 7. They show that a maximum rise in porewater pressure over the whole trail was recorded as 6 to 8kN/m^2. A minimal porewater pressure increase was recorded for the 20kN/m^2 passes and a settlement of 1mm was recorded for the 40kN/m^2 passes. The maximum settlement recorded for the sections of the test trail underlain by normally consolidated cohesive soil was 26mm.

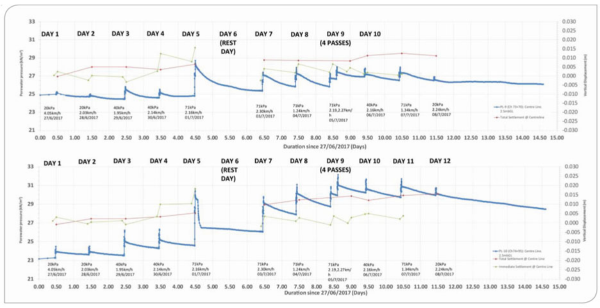

Figure 7. Graphical plots of dynamic embankment trial settlement and pore pressure increase

Settlement and pore pressure monitoring was undertaken over the full 4-year operation of the haul road as part of the project Operation and Maintenance Plan. Apart from two short stretches of haul road of 200 metre total length where settlement up to 100mm was experienced the majority of the haul road where it was underlain by normally consolidated cohesive soils experienced settlements of less than 50mm. where settlements of these magnitudes occurred the running surface of the haul road was re-levelled during the winter period where no module movements took place. Where the haul road route corridor was underlain by granular soils settlements of less than 30mm were experienced over the whole operating life. Pore pressure increase was not measured greater than 3kN/m^2 for any single module pass during the operation of the haul road.

The initial theoretical modelling and subsequent haul road performance indicate that current live traffic load modelling applied to geotechnical design is significantly conservative as postulated by Nowak and Gilbert (2015).

4 DISCUSSION

Traditionally, live traffic loading applied to earthworks and earth structures has been taken from the approach of structural engineers where the applied load is in direct contact with the structural element being designed, the bridge deck.

The application of the approach developed on the A14 Cambridge to Huntingdon Improvement project considers the reduction of live traffic loading in geotechnical modelling of earthworks and structure foundations but does not fully address the conservatism currently being applied.

The Tengiz FGP dynamic modelling results indicate that the current geotechnical modelling of a quasi-static load is significantly conservative. This may be for one or a combination of a number of reasons such as:

- The transient nature of the live traffic load does not impart the full stress distribution with depth to develop before it passes the point of application.
- The Boussinesq approach of pressure distribution with depth is not applicable to transient loading.

- The practice of considering vehicle axle, tyre and track loads as a UDL of the plan area of the vehicle/plant whilst applicable to the design of bridge decks is very conservative if applied to geotechnical design

It is more likely, in actuality, that vehicular loading is applied only over the footprint of the tyres/tracks forming a very shallow pressure bulb which occurs wholly in the high stiffness pavement construction and does not influence the earthwork below sub-grade. If this were not the case, there would have been significant settlement issues for highways and rail earthworks over their design life which has not been the case.

It should also be noted that normal traffic loading is intermittent and not sustained vehicle loading. The situation illustrated in Figure 8 is that of Operation Stack on the M20 motorway in Kent, UK where lorries are queued if there is disruption in Cross Channel access to France. This loading is, however, temporary for a few days until the disruption has cleared and represents a very small percentage of the design life of highway infrastructure.

Figure 8. Operation Stack on M20 motorway, UK

5 CONCLSIONS

In conclusion the following can be drawn from the examples outlined above:

- Loads generated by structures engineers are conservative as they seek to prevent loss of service and a less conservative, ambient traffic loading involving the use of the Frequent Case in EN1990 is more representative if it is required by the analysis.
- The term quasi-static is a modelling construct used by structural engineers to simplify analysis of a cyclic loading. The term 'quasi-static' in geotechnical engineering has a different context.
- Comparison of theoretical settlement and pore pressure with actual values on Tengizchevroil project indicate that the concept of pore pressure increase on loading, whilst relevant for a sustained load such as a trial embankment, is extremely conservative when considering traffic loading which is transient and cyclic.
- Additionally, it is conservative to consider a 'quasi-static' traffic loading as equivalent to a permanent loading in relation to induced settlement. As the Tengizchevroil project live trial showed there was significantly less settlement than the theoretical calculation.
- If theoretical settlement calculations accurately reflected the loading from vehicles there would be earthworks failure of major infrastructure over its design life

As we strive to reduce carbon in the construction industry design conservativism should be challenged even if it is captured in Codes of Practice.

It is suggested that live traffic load is omitted from any calculation of settlement and considered with respect to stability as an exceptional load case where initially no live load is applied. A parallel analysis should then be carried out to determine the effect of the application of the live load in a conservative way. An engineering judgement can then be made regarding the variance of Factor of Safety and a decision on the analysis to be adopted based on the risk to the earthwork given the conservative approach of live load application.

The same approach could also be adopted for finite element modelling where the model is run with no applied live load and then live load is applied.

This would allow the designer to investigate what impact applied live load has on retaining wall reinforcement/ sheet pile wall section, reinforcement length of reinforced soil structures and the stability of earthworks slopes and make a value judgement on its actual impact on the earthworks or earth structure over its design life.

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