TOWARDS PRACTICAL MODELING OF INTEGRAL-ABUTMENT BRIDGES UNDER LONGITUDINAL LOAD

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Abstract:
Bridges with integral or semi-integral abutments are increasingly favoured both in New Zealand and internationally. However analysis of bridge structures which incorporate such abutment structures is more demanding, particularly under longitudinal load.

Longitudinal loads for which such bridges must cater include monotonic retention loads, daily and seasonal temperature cycles, episodic effects such as braking and traction, and more extreme situations such as earthquake-induced vibration, liquefaction and lateral spread.

The Bridge Manual administered by the New Zealand Transport Agency permits the use of relatively long bridges with integral or semi-integral abutments only where their design is supported by "rational analysis". Other national bridge prescriptions also limit the length of bridges with integral or semi-integral abutments.

An approach to the analysis of such bridges under longitudinal load is proposed. This approach seeks to draw on information from a number of sources, and to combine this information in a manner which is practical; which gives confidence in the predicted structural demands; and which satisfies the requirements of documents such as New Zealand's Bridge Manual.

Introduction

Bridges with integral or semi-integral abutments provide improved ride quality in comparison to more conventional bridges which use simply-supported spans, and offer modest improvements in structural efficiency under traffic load. Omitting (or at least minimizing) bearings and expansion joints also reduces construction cost, and helps to minimize whole-of-life cost by reducing direct costs, traffic management and traffic disruption associated with maintenance and replacement of bridge hardware.

For such reasons bridges with integral and semi-integral abutments are increasingly favoured both in New Zealand and internationally. However analysis of bridge structures which incorporate such abutment structures is more demanding, particularly under longitudinal load.

Section 4.11 of New Zealand's *Bridge Manual*[1] reflects the inherent advantages of such construction by explicitly accepting integral or semi-integral concrete bridges of up to 70m length, and steel bridges up to 55m length. The use of longer bridges with integral or semi-integral abutments is also permitted providing that such proposals are supported by rational analysis.

The UK Highways Agency goes further, albeit in an environment where de-icing salts pose increased risks to bridge hardware: clause 1.1 of BA 42/96 *The design of integral bridges*[2] indicates that "bridge decks up to 60m in length and with skews not exceeding 30^o are generally required to be continuous over intermediate supports and integral with their abutments."

Other jurisdictions also recognize the merits of such construction, but impose similar constraints.

We understand that the New Zealand requirement reflects a survey of the performance of existing bridges which function as integral or semi-integral structures, irrespective of the designers' original intent; and that the current length limits reflect the limits of integral-type bridges available for inspection when the survey was conducted. At the time of the survey longer bridges tended to incorporate expansion joints.

A number of bridges with integral abutments have been built in New Zealand relatively recently and have performed well. The longest such bridge for which we have had design responsibility is some 150m long, built in 2001. Longer integral bridges have been reported internationally, notably one bridge of 323m length in Tennessee.

This paper postulates an approach to the assessment of structural demands on the abutments and the piles and superstructure members of integral and semi-integral bridges. This approach reflects one strand of our office practice, and is presented as a candidate which may satisfy the *Bridge Manual* requirement for "rational analysis".

Background

All traffic bridges are subject to a range of longitudinal actions, including the effects of temperature variation and vehicle braking and traction.

- With a conventional (non-integral) bridge, longitudinal loads are typically resisted by the piers; longitudinal movements are catered for by strategically placed expansion joints; and bearings accommodate differential longitudinal movements between the superstructure and the supporting structure. Both joints and bearings are sized to allow the requisite relative movement between superstructure and substructure.

- With integral or semi-integral abutments, longitudinal loads are typically resisted by a combination of pier resistance and increased soil retention pressure on the abutment wall towards which the load is directed. Potential longitudinal movement is partially *restrained* by the abutment structure and the soil bearing, and partially *accommodated* by movement of the abutment into the retained soil as the retention pressure increases.

In "non-seismic" areas such as the UK the resistance to longitudinal movement which an abutment structure offers to longitudinal movement is seen as a problem; where bridges must cater for significant seismic loads, abutment resistance can offer substantial benefits.

- In the UK the "temperature problem" faced by integral bridges has been investigated by England et al and reported in their book *Integral bridges: a fundamental approach to the time-temperature loading problem*[3]. This reference recommends a relationship between abutment backwall pressure and displacement. This relationship has been incorporated in the UK Highways Agency BA 42/96 requirements for the design of integral bridges.

- In places such as New Zealand, Japan and some areas of the USA earthquake demands can dominate the longitudinal loads which bridge structures must resist. Structural demands associated with earthquake can include any or all of:
  - "inertial" loads generated by seismic action on the seismic weight of the bridge superstructure;
  - additional "inertial" loads due to seismic action on soil retained by bridge abutments;
  - "kinematic" loads generated by differential movement of bridge foundations and surficial soils;
  - changes in soil stiffness and strength associated with earthquake-induced soil liquefaction;
  - "lateral spread" loads imposed by competent surficial soils migrating towards "low-points" such as river channels.

Soil bearing on backwalls of integral and semi-integral abutment bridges can make a major contribution to the resistance of any of these loads. Hence in temperature-dominated applications soil pressures on integral abutment backwalls *impose* a load on the bridge structure as they increase to resist free thermal expansion, but in earthquake-dominated applications soil pressures can provide substantial *resistance* to seismic load.

Hence integral construction can be seen as penalizing non-seismic situations but benefiting seismic situations.

The need to be able to model the seismic behaviour of integral / semi-integral abutment construction has long been recognized:
  - In 1990 Wood & Elms[4] presented studies of backwall pressure distribution at various displacements of walls translated or rotated into the retained backfill.
  - In 1994 Maroney & Chai[5] presented a relationship between backwall pressure and ratio of displacement to wall height which correlated well with the California Department of Transport (Caltrans) recommendations for wall stiffness at very small displacements and maximum wall resistance at high displacements. This work has been reported by Priestly Seible & Calvi[6] and elsewhere. Reporting is not always accurate, and limitations in the data provided make it difficult to draw any general conclusions.

- The 2003 *Recommended LRFD guidelines for the seismic design of highway bridges* (MCEER / ATC-49, 2003)[7] recommended using conventional methods for assessing passive resistance of soils retained by bridge abutments (including the effects of wall friction), and give rudimentary data on presumptive relationships between the stiffness, strength, and geometry of abutment backwalls where they bear on the retained soil.

The data provided by such studies can be used to substantiate the analysis of specific bridges or to corroborate methods of analysis.

Analysis tools

The proposed approach is not specific to a single method or analysis tool. We have used a variety of hand methods and software packages over a number of years, but our current practice is based on the use of WALLAP[8].

WALLAP's normal use as a specialist retaining wall package does not make it an obvious candidate for the purpose of assessing structural demands on integral bridge abutments, but it offers a range of useful features. Our previous use of WALLAP for the analysis of structures such as deep basements built top-down, and observation of the behaviour of the structures so designed gave confidence in the program's capability and reliability for the realistic modeling of situations where soil-structure interaction is of fundamental importance. This adds a less tangible but equally valuable advantage.

Hence although the following description is based on WALLAP, the approach presented is equally applicable to other packages.

WALLAP is based on a single vertical structural element. This limit to the sophistication of modeling is offset by a number of useful features:

- *multiple layers of soil* on one or both sides of this element;
- *progressive earthworks operations* such as construction of embankments, fill and/or cut works necessary to construct spill-through abutment treatments etc;
- *sequential effects*, whether related to construction sequence or load history;
- *loads and moments can be applied and removed* to assess the impact of ratcheting movements or other cumulative effects;
- *elastic-plastic behaviour of* <u>*soils*</u> subject to either active or passive pressures is a long-standing feature;
- *elastic-plastic* <u>*structural*</u> *behaviour* is a recent addition;
- *variation in structural properties* up the height of the structural element;

- *variation in soil properties* to simulate the impact of varying drainage conditions, strain rates or time-related effects such as soil liquefaction on individual load cases;

- *early stage output data* can be used as key data for use in later stages;

- *sensitivity analysis* can be readily incorporated.

WALLAP is transparent: the impact of each stage can be assessed in isolation; and it is simple to establish the impact of individual variables on that stage. We value the opportunity this provides for the analyst to develop familiarity with the effects of individual variables, particularly for such applications where soil-structure interaction has a major impact on structural behaviour.

Corroboration

WALLAP has been used to simulate the tests variously reported by Wood & Elms and England et al to verify whether it can be used with confidence for more demanding purposes.

Wood and Elms present data for model walls translated and rotated into retained gravelly sands.

- The approach suggested in this paper gives marginally low estimates of capacity for all cases when compared with test results.
- Displacements predicted by WALLAP for translated walls (at suggested upper bound stiffnesses) agree well with test data for dense sands, but predicted displacements become increasingly larger than test displacements as the relative density of the backfill decreases.
- Displacements predicted by WALLAP for rotated walls again tend to be higher than test results for the dense sand tested.

Data describing the test soils used by Wood and Elms is limited, and inaccurate interpretations may account for some of the disparities. The translation tests were cyclic, and it is also possible that the improvement of properties reported by England et al resulted in boosted test results. In either case this comparison serves to emphasise the importance of bracketing analysis predictions using sensitivity study.

England et al report the results of a series of model walls rotated into the dense sands retained by the wall, and recommend a relationship between pressure and rotation magnitude. Again tests are cyclic. Plotting test points against the proposed relationship and the WALLAP predictions (again using upper bound Young's Modulus values) gives good agreement for both strength and displacement.

The disparities between test and predicted behaviour should be noted. The probable cause of inappropriate interpretation of soil data is equally possible in real cases, and reinforces the need for sensitivity study.

Other relationships presented by Maroney & Chai or MCEER / ATC-49 are more difficult to emulate with the level of supporting data provided. However either (or preferably both) can be readily used in hand methods to approximate or review a more comprehensive assessment. For example the MCEER / ATC-49 relationship gives good correlation with both test and WALLAP-predicted data for the Wood and Elms test using dense sand, slightly under-predicting strength and over-estimating displacement.

We suggest that the accuracy of any analysis tools used for purposes such as those described here should also be verified by simulating actual tests, to give confidence in the tool itself, and in the interpretation of soil and structural properties for inclusion in the analytical model.

Improved availability of benchmark test data for this purpose would be valuable.

Proposed modeling sequence

The structural system at any bridge abutment under longitudinal load can be visualized as:

- *the transverse structural element* of abutment beam and backwall upstand;
- *the abutting deck structure*, which may both impose or resist translation and/or rotation of the abutment;
- *the supporting foundation*, which may again both impose or resist translation and/or rotation of the abutment, whether vertical support is provided by piles or strip footings.

This system interacts with the soils to each side of the abutment upstand / beam / piles, and needs to be simulated by the analytical model. This model also needs to be capable of modeling the various applied loads, ideally in the sequence to which the real structure will be exposed to these loads (in the unlikely event that this is known with confidence).

For example the successive stages of a simple single-span spill-through integral bridge built "top-down" as used below to illustrate the proposed approach:

Construction:

- Construct approach embankments
- Construct piles
- Construct bridge superstructure, including modeling stiffness of strut between abutments under symmetric loads

- Cut final earthworks profile under bridge

Symmetric loading:

- Apply & remove (absolute) temperature increase / check effect
  (eg ascertain whether soil and structure remain elastic; identify any ratcheting effects)

- Apply & remove (absolute) temperature decrease / check effect

- Apply & remove (differential) temperature increase / check effect

Minor non-symmetric loading:

- Apply & remove embankment surcharge loads emulating traffic carriageway loading / check effect

- Apply & remove braking & traction loads / check effect

Major non-symmetric loading:

- Apply longitudinal seismic load toward retained soil / measure deflection to evaluate stiffness & period & seismic coefficient implicit in load modeled / remove longitudinal seismic load / check effect

- Revise strut stiffness to simulate stiffness of abutment forced into soil beyond

- Apply longitudinal seismic load imposed by retained soil / check stiffness & period & seismic coefficient implicit in load modeled / remove longitudinal seismic load / check effect

- Change soil properties to reflect liquefied soil

- Repeat application / removal of seismic loads (in each direction) / check stiffness and modify strut properties as appropriate

- Apply lateral spread loads (after Cubrinovski[9]), in say 10% stages; check displacements against predicted "free-field" lateral spread displacements;
  check structural demands remain elastic.

This process provides a single compact analysis file which includes the cumulative effects of soil-structure interaction at each sequential stage; and which facilitates examination of the raft of pertinent effects in a compact and consistent manner.

This file can be used to assess the effects of most structural actions directly. It can also be used to develop load-deflection "pushover" curves for use in either force-based or displacement-based assessment of seismic demands.

The output is simple and compact, but care is necessary in management of the analysis to ensure that the assumptions implicit in each stage are valid, and variables are selected at appropriate levels. Careful scrutiny of the results is important, utilising a jaundiced eye in review of input and output data.

Sensitivity analysis

Approaches such as this draw on both soil and structure properties, some of which are not generally known with precision. Stiffness and strength of both soil and structure introduces further uncertainties, and even loads are based on a range of assumptions. Hence sensitivity analysis is important.

The use of WALLAP is amenable to very simple sensitivity study, as described above. It is our practice to undertake both “stiff” analysis and “flexible” analyses, taking the strength and stiffness properties towards what we see as the credible maxima and minima respectively. We do not generally mix and match maximum and minimum criteria for different variables, for reasons of practicality.

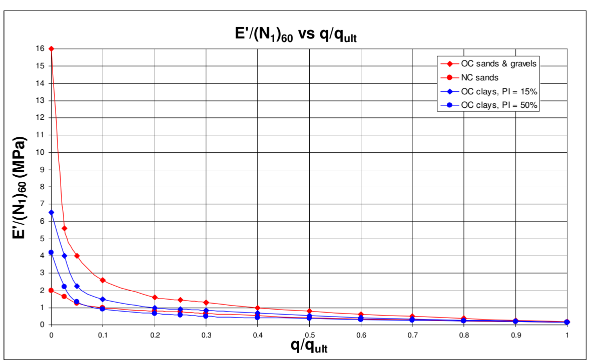
Soil stiffness

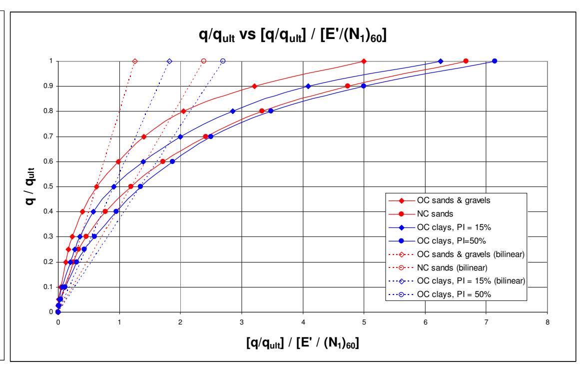
Soil stiffnesses reported in the literature vary substantially, with variation in large part contingent on the soil stress levels and strain rates to which they are subject.

Typically seismic effects dominate the longitudinal demands on bridges in this country, and pressures on the backwalls of integral bridges tend to approach passive levels.

Hence for bilinear elastic-plastic analysis of integral structures we typically take soil stiffnesses derived from those predicted by Stroud as reported by Potts & Zdravkovic[10], at about $q/q_{ult} = 0.5$ for our “best estimate” models.

Different relationships can be developed, but in terms of SPT $(N_1)_{60}$ rustic extrapolation of the Stroud data to give smooth curves for both following plotted relationships, and low stiffness as stress levels approach maxima gives:





This material yields the following approximate data. While 2 significant figures are given this is optimistic:

	q/q_{ult}			
	0.10	0.25	**0.50**	0.7
$E'/(N_1)_{60}$ for :				
o Over-consolidated sands & gravels	2.6	1.45	**0.80**	0.50
o Normally-consolidated sands	1.0	0.75	**0.42**	0.29
o Over-consolidated clays, PI = 15%	1.5	0.93	**0.55**	0.35
o Over-consolidated clays, PI = 50%	0.9	0.60	**0.37**	0.28

Borrin shows that values of Young's Modulus for undrained cohesive materials tend to be about 30% higher than for drained cohesive materials, such as those provided above.

This data appears comparable to other stiffness data in the literature which is correlated to load level, and tends to encompass the data which is quoted without reference to stress level. For sensitivity study we typically take soil stiffness at 150% and 75% of the $E'/(N_1)_{60}$ values at $q/q_{ult} = 0.50$. The data above suggests that this covers a good range.

Soil strength

For the assessment of active and passive soil coefficients we typically defer to WALLAP's default values based on cohesion and friction angle as predicted by WALLAP after Coulomb or EC7, or directly from NavFac 7.2[11] Fig 5 page 7.2 – 66. Larkin[12] gives a useful series of plots of seismic passive pressure coefficient limits, based on log-spiral failure surfaces, for varying horizontal and vertical seismic accelerations. For each source we tend to assume a ratio of wall friction to soil friction angle of 0.5, as recommended by clause 3.3 of BA 42/96 for integral bridge abutments.

Soil strength is typically known with more confidence than is soil stiffness, but clauses 2.8 and 2.9 of UK Highways Agency BA 42/96 recommend using a (partial) load factor of 1.5 for passive earth pressure, coupled with (partial) materials factors of 0.5 for "favourable" load effects and 1.0 for "disadvantageous" load effects. These could be considered to compound to effective factors of 0.75 and 1.5 respectively. Maroney & Chai report Caltrans using a multiplier of 1.54 on conventional passive earth resistance to allow for the high rates of strain expected under earthquake. Because conventional passive resistances are typically developed from low estimates of soil strength parameters we tend to use low and high multipliers of about 1 and 1.5 on our best estimates of soil strength.

Clause 3.2 of BA 42/96 notes that granular fill behind abutment backwalls is effectively densified by in-service cyclic movements even if it is placed in a loose condition, and recommends that c'_{peak} and ϕ'_{peak} should be based on the properties of soil compacted at optimum moisture content to a dry density of 95% maximum dry density. This appears to be based on the work of England et al, who observe that thermal ratcheting produces long-term soil stresses which are "*little affected by the initial density of the backfill material or by the season (summer, winter etc) during which the structure enters service*".

This is a very convenient finding, particularly if initial soil density is tailored towards this long-term stable level. It is convenient that the presumptive strength and stiffness of integral abutments suggested by MCEER/ATC-49 is also tagged to backfill of 95% maximum dry density.

Structural stiffness

Variation in stiffness of structural members is typically less than for soils, but significant differences remain very evident both in practice and in recommendations of codes of practice and authoritative references.

Priestley, Calvi & Kowalsky[13] have identified variation of the effective flexural stiffness of members such as pier stems and piles between 12% and 86% of gross concrete properties. Dominant variables are identified as reinforcement content and axial load level. For typical reinforcement contents of about 2%, stiffnesses are very similar to the recommendations of NZS 3101:2006[14] Table C6.6, but the variation of stiffness with these key variables presented in Priestley, Calvi & Kowalski is very helpful.

The data produced by Fenwick & Megget[15] shows the same trends but tends to give slightly lower stiffnesses. This is consistent with the stiffness reduction they identify as a result of their explicit consideration of the effects of shrinkage and creep strains prior to application of short term loading.

Plotting data from both sources suggests that stiffness variation is dominated by reinforcement content rather than axial load until average axial concrete stresses approach 0.3 f'_c.

For our “best-estimate” of structural stiffness of reinforced concrete pier pile members we typically use the data produced by Fenwick & Megget. For reinforced concrete bridge pier / pile flexural members this typically gives effective stiffness of about 35% of gross concrete properties. Stiffness increase by a factor of about 1.5 for sensitivity study tends to capture other authoritative recommendations for normal member proportions. For prestressed concrete members we typically use 100% of gross concrete properties.

Structural strength

Structural strengths are relatively well-defined and consistently-defined by codes of practice.

Structural actions

Structural demands under non-seismic loads can be readily assessed using the tools described above.

Structural actions imposed by earthquake need to be assessed with care. If a quasi-static approach is to be taken, then inertial, kinematic, and lateral spread effects need to be considered separately and carefully. We see the material developed by Misko Cubrinovski as being of fundamental value for such analysis, in part because it is simple; but more importantly because it has been calibrated by the experience gained in the Kobe earthquake, and corroborated by rigorous analysis which is beyond the practical reach of most practitioners.

- *Inertial effects* on pre-liquefaction and post-liquefaction behaviour due to the interaction of earthquake and superstructure mass tend to differ dramatically as a result of changes in soil stiffness. However it is our experience that envelope structural actions due to the inertial effects of earthquake loading under pre-liquefaction and post-liquefaction conditions are surprisingly (and comfortingly) insensitive to the dramatic variation in soil stiffness, with the compounding trends of liquefaction to lengthen period; to increase depth to "effective fixity" of piles; and to increase P-δ effects tending to compensate.

  Our experience in making this observation is limited, and it does not justify ignoring the need for sensitivity study. Instead it provides a background against which any apparent differences in structural demands of significant magnitude should be examined with some care.

  The recommendations provided by Cubrinovski for the reduction in soil stiffness produced by soil liquefaction provide clear and cogent guidance which can be used for pseudo-static analysis of inertial effects.

  These can be modeled in WALLAP, iterating to determine the data set of longitudinal seismic displacement, initial or secant stiffness, fundamental period, period-specific loads, and (again) longitudinal seismic displacement to give closure.

  Structural actions are then able to be extracted from the WALLAP model.

- *Kinematic effects* due to the interaction of earthquake and the soil surrounding the piles appear less accessible in the literature. Kinematic effects will certainly impact on pile demands. The extent to which they will do so will be contingent on whether or not the response of superstructure and soils surrounding the piles are in phase. Intuitively it seems less significant than either the inertial or lateral spread "phases" of response, but this is a personal and unsubstantiated supposition.

- *Lateral spread* displacements can be substantial. Structural demands due to significant lateral spread displacements are unlikely to fall within the envelope of inertial effects; they can form the dominant load case; and they are monotonic in direction – there is no trend for recovery of displacements or reduction of the associated structural demands.

  The Cubrinovski recommendations can again be used. They include suggestions both for soil stiffness, and for the maximum pressure which a body of soil displacing due to lateral spread can impose on a pile.

Cubrinovski recommends that the expected lateral deflection profile should be applied to a pile under investigation via a non-linear bed of springs.

WALLAP does not have such a facility; neither would we normally expect to have access to a predicted profile of “free-field) lateral spread displacement with depth. Instead it is our practice to impose the maximum predicted passive pressures in a series of equal steps so the development of displacement with load can be tracked.

If cumulative displacement exceeds estimated lateral spread movement then the maximum passive pressure may not be actually applied.

Maximum structural actions can be extracted from the analysis when either the maximum anticipated loads or maximum anticipated displacements have been imposed.

Applications

We have used this approach recently in both design and review of a number of bridge structures. This includes bridges with and without integral abutments.

Review has afforded opportunity to compare the conclusions of the suggested approach when used in a “review” context, with conclusions of a completely independent and rigorous “design” analysis. Both design and review analyses drew on identical structural proposals and the same soil investigation data. Interpretation of the soil investigation data was independent, but led to agreement of base soil properties to be adopted. Structural modeling was completely independent. Conclusions were comparable. It is difficult to be sure which approach may be the more credible, but the use of WALLAP appeals because:

- consecutive stages of construction and loading can be readily simulated;
- modeling is straightforward and transparent;
- comprehensive sensitivity analysis is readily achieved.

Conclusion

The approach suggested in this paper to the modeling of longitudinal actions on bridge abutments requires care in management of the analysis process, but it appears to be practical, compact and flexible. It has particular appeal for the modeling of abutment structures which are integral or semi-integral, and / or those which may be exposed to liquefaction and lateral spread, as well as more routine earthquake exposure.

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