TRANSPORT RESEARCH LABORATORY

Seasonal thermal effects over three years on the shallow abutment of an integral bridge in Glasgow

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Executive Summary

In an integral bridge, the abutments are structurally connected to a continuous deck, thus avoiding the use of bearings as required in more conventional road bridges. In turn, this obviates the need for deck joints and hence reduces the possibility of road de-icing salts causing long term damage. However, seasonal thermal movements of the deck cause interactions between the bridge and the surrounding soil. To obtain full advantage from the use of integral bridges and minimise risk of overstressing the abutments, it is important to obtain a better understanding of the soil structure interaction.

Monitoring of an integral bridge abutment in Glasgow (M74) was commenced during 1993. The bridge, which is of approximately 60m span, was constructed with shallow integral abutments, three intermediate supports and a continuous twin deck. The results during construction and up to Feb 1995 have been reported in TRL R178. This report describes the results of the monitoring from February 1995 to January 1998.

Measurements between the abutments of the bridge showed that the deck length had continued to change with temperature with a coefficient of thermal expansion of about $9 \times 10^{-6}/^{o}C$. The main emphasis of the report is on the lateral stress development behind the abutment which results from the cyclic loading caused by this movement.

The results confirm that high stresses behind shallow abutments are likely in the long term. Further backfill stress measurements are required for an integral bridge which has been in-service for more than a decade or better quantification of wall friction in integral bridges, to enable further refinement of the current recommendations of BA42.

1 Introduction

Earth pressures acting behind an integral abutment are likely to increase progressively with time because of seasonal cycles of thermal expansion and contraction of the bridge deck (Card and Carder, 1993). The problem is likely to be particularly acute with granular backfill to the abutment where particle orientation and densification is likely to lead to both increased lateral loading on the abutment wall and an increased axial deck load. This mechanism has been demonstrated by centrifuge and analytical work simulating long term behaviour carried out by Springman, Norrish and Ng (1996) and Hird and Djerbib (1992). England and Dunstan (1994) have also investigated the effect of 'strain ratcheting' induced in granular soils by many cycles of thermal movement and reached the conclusion that lateral stresses will escalate. It is nevertheless generally acknowledged that integral bridges will be effective in reducing the high maintenance costs caused by damage to the bearings and expansion joints by penetration of road de-icing salts and the Highways Agency is encouraging their use following the issue of BD57 (DMRB 1.3).

To provide more design advice on this topic, monitoring of an integral bridge abutment carrying the M74 across Carmyle Avenue (A763, Glasgow) was commenced during 1993. The bridge of about 60m span was constructed with shallow integral abutments, three intermediate supports and a continuous twin deck. The results during construction and up to February 1995 have already been reported (Darley, Carder, and Alderman, 1996). This update describes results of the monitoring from February 1995 to January 1998.

Instrumentation was installed to measure lateral earth pressures acting on the retained face of the abutment, tilt and movement of the abutment, and changes in length and level of the bridge deck with temperature. Additionally stations were installed beneath the run on-slab to determine settlement of the backfill behind the abutment.

The instrument layout is shown in Figures 1 and 2; more details of the instrumentation are reported by Darley et al (1996).

2 Measurements

2.1 Lateral movement of the abutment and changes in deck length

Figure 3 shows the profiles of lateral movement with depth determined from inclinometer surveys and the average deck temperatures at eight dates. The results show that the deck temperature for January 1997 was very close to those of February 1995 and February 1996 and the three lateral movement profiles (F, A and D in Figure 3) were almost identical. The profiles G, B and C for June 1997, June and August 1995 respectively showed the abutment to have moved about 4mm from its February position for a temperature change of about 16^0C. The movement profile H for January 1998 shows the top of the abutment to have moved some 2mm further towards the central pier than was measured in the three previous winters (profiles A, D and F). The results in Figure 3 also confirm the previous findings of Darley et al (1996) which indicated that some sliding was occurring between the base of the shallow concrete abutment and its soil foundation.

Figure 4 shows the variation with deck temperature of the lateral movement of the top of the abutment and the base of the concrete abutment calculated from the inclinometer data assuming base fixity of the inclinometer tube. The magnitude of the lateral movement at the top of the shallow concrete abutment was larger than at the base. A linear regression analysis of base movement against deck temperature is shown in Figure 5 and gave best fit slopes of 0.10mm/^{o}C and 0.09mm/^{o}C for data retrieved before and after February 1995 respectively. The movement of the base was probably accompanied by a combination of elastic deformation of the soil foundation and some sliding of the concrete abutment. It was not possible to quantify the relative proportions of the movements due to each mechanism.

Linear regression analyses of the lateral movement of the top of the abutment, as measured by the inclinometer survey (with base fixity of the tube assumed), against average deck temperature is given in Figure 6. The figure shows two 'best fit' linear regressions of lateral movement of the top of the abutment against mean deck temperature. The first regression which comprised the data prior to February 1995 gave a slope of 0.248mm/^{0}C, whilst the best fit for the data obtained between February 1995 and January 1998 gave a slope of 0.239mm/^{0}C. On dividing by the bridge half-span these slopes are equivalent to coefficients of thermal expansion of the deck of 8.2×10^{-6}/^{o}C and 7.9×10^{-6}/^{o}C respectively. These values can be compared with the 9.2×10^{-6}/^{o}C reported by Darley et al (1996) during the construction period and, as backfilling behind the abutments was one of the last activities, this particular coefficient can be considered to mainly represent unconstrained deck expansion.

On the basis of the small decrease in apparent coefficient of thermal expansion which has occurred with time, it could be concluded that some densification of the backfill and hence resistance to lateral movement of the abutment is occurring as thermal cycling continues. However calculation of these coefficients is very sensitive and small movement changes (<1mm) are significant. Such small changes could also be a consequence of some movement of the base of the inclinometer tube. Alternatively they could be caused by difficulties in measuring to this accuracy; tests on the reproducibility of the inclinometer measurements showed that lateral movements at the top of the tube relative to its base could be determined to better than ±0.5mm.

The relationship between the change in deck length measured using the Geomensor electronic distance measuring system and the mean deck temperature is shown in Figure 7. The best fit regression analysis for the 1995 to 1998 data gave a slope of 0.66mm/^{0}C compared to 0.54mm/^{0}C for the 1994 to 1995 data. When divided by the bridge span, respective coefficients of thermal expansion of 10.9×10^{-6}/^{o}C and 9.0×10^{-6}/^{o}C are obtained for

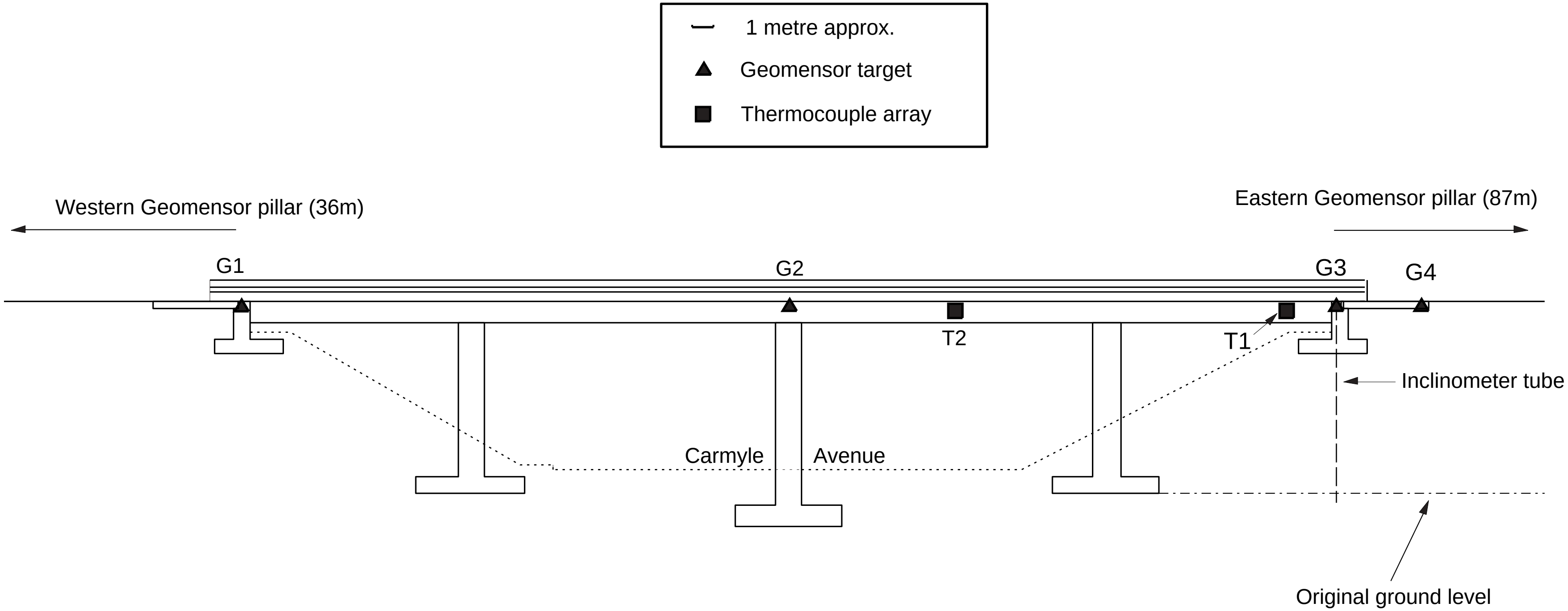

Figure 1 Section through Carmyle Avenue bridge

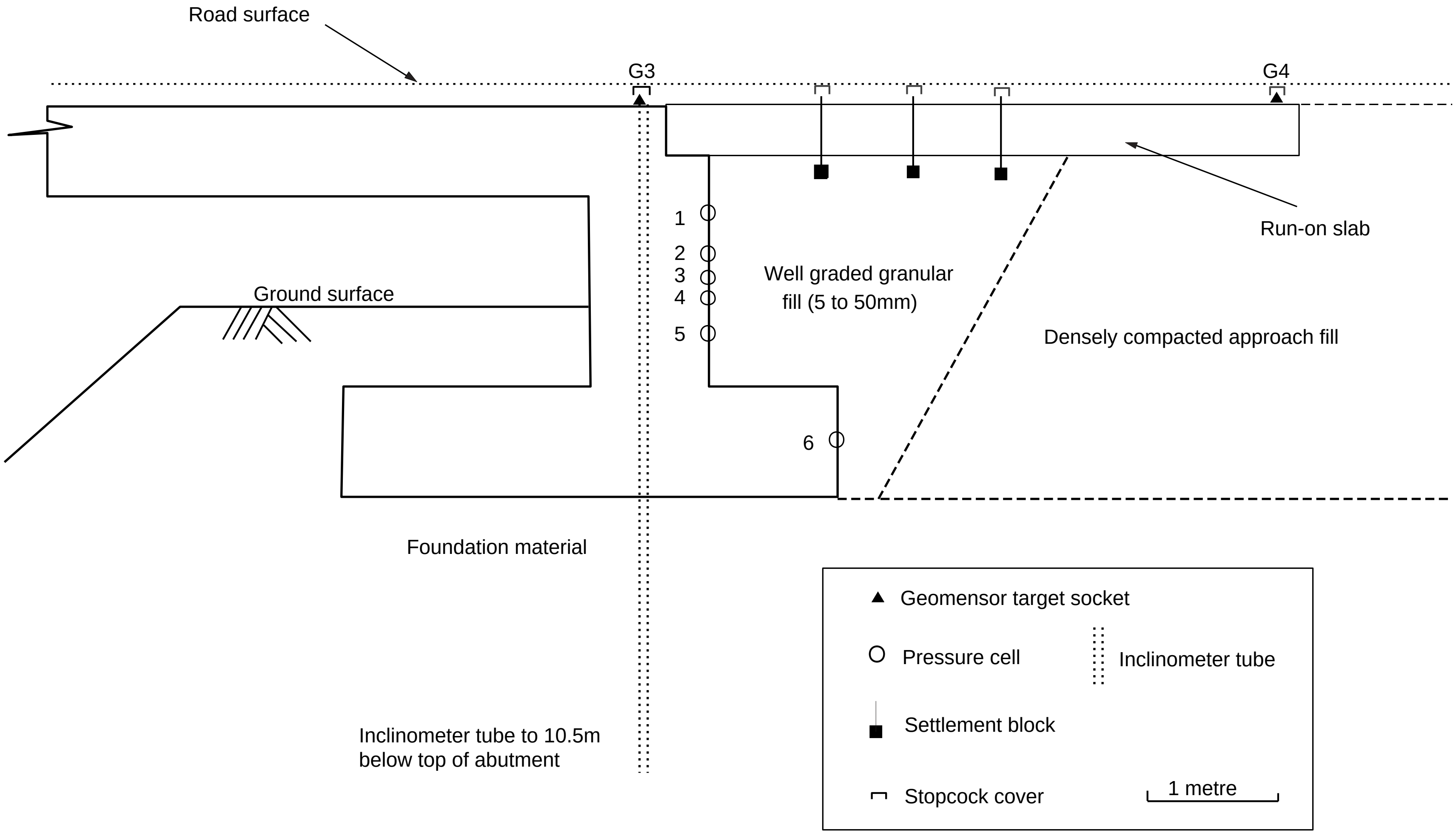

Figure 2 Section through instrumented integral abutment

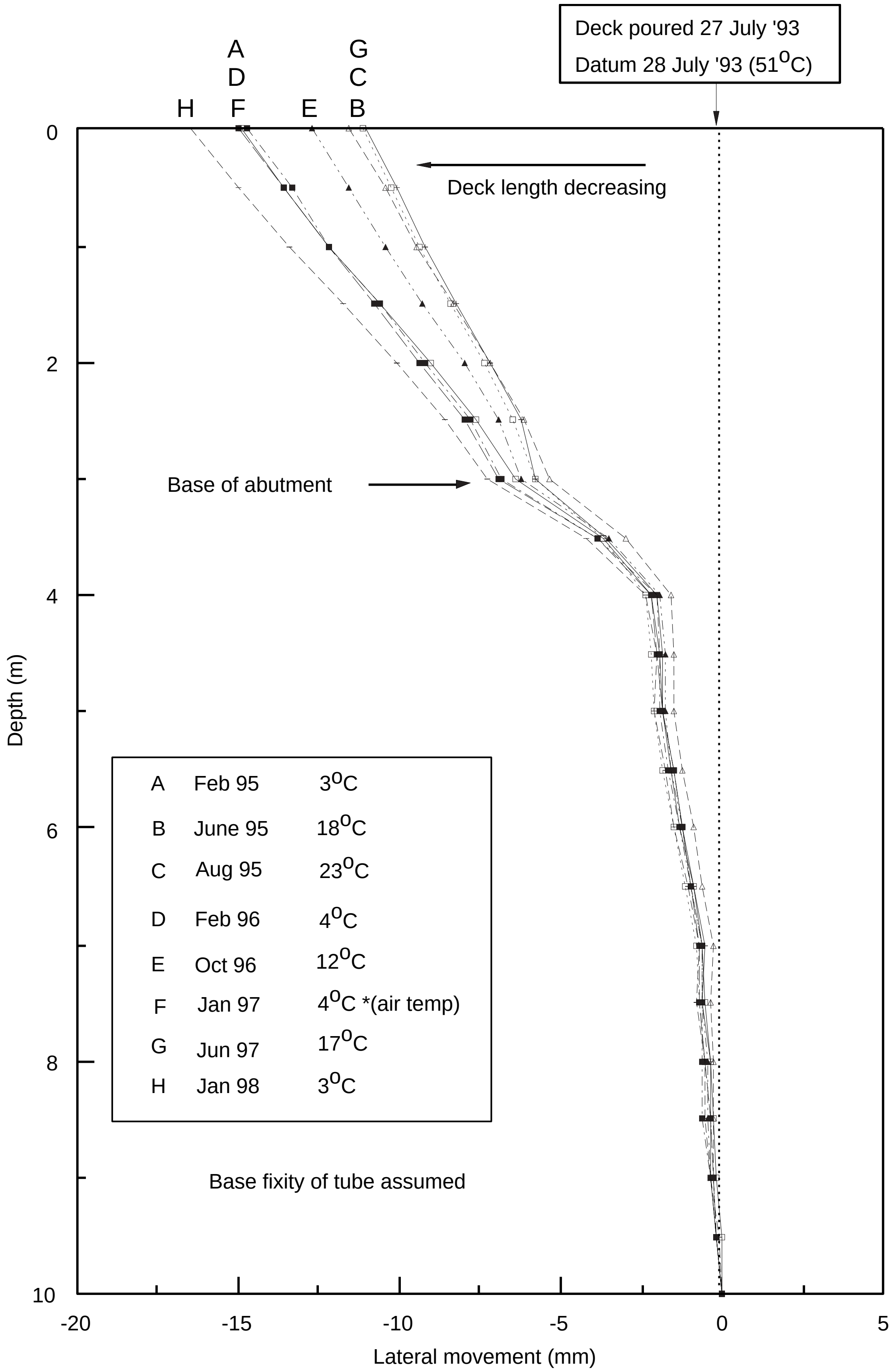

Figure 3 Long term movement of abutment measured by inclinometer (February 1995 to January 1998)

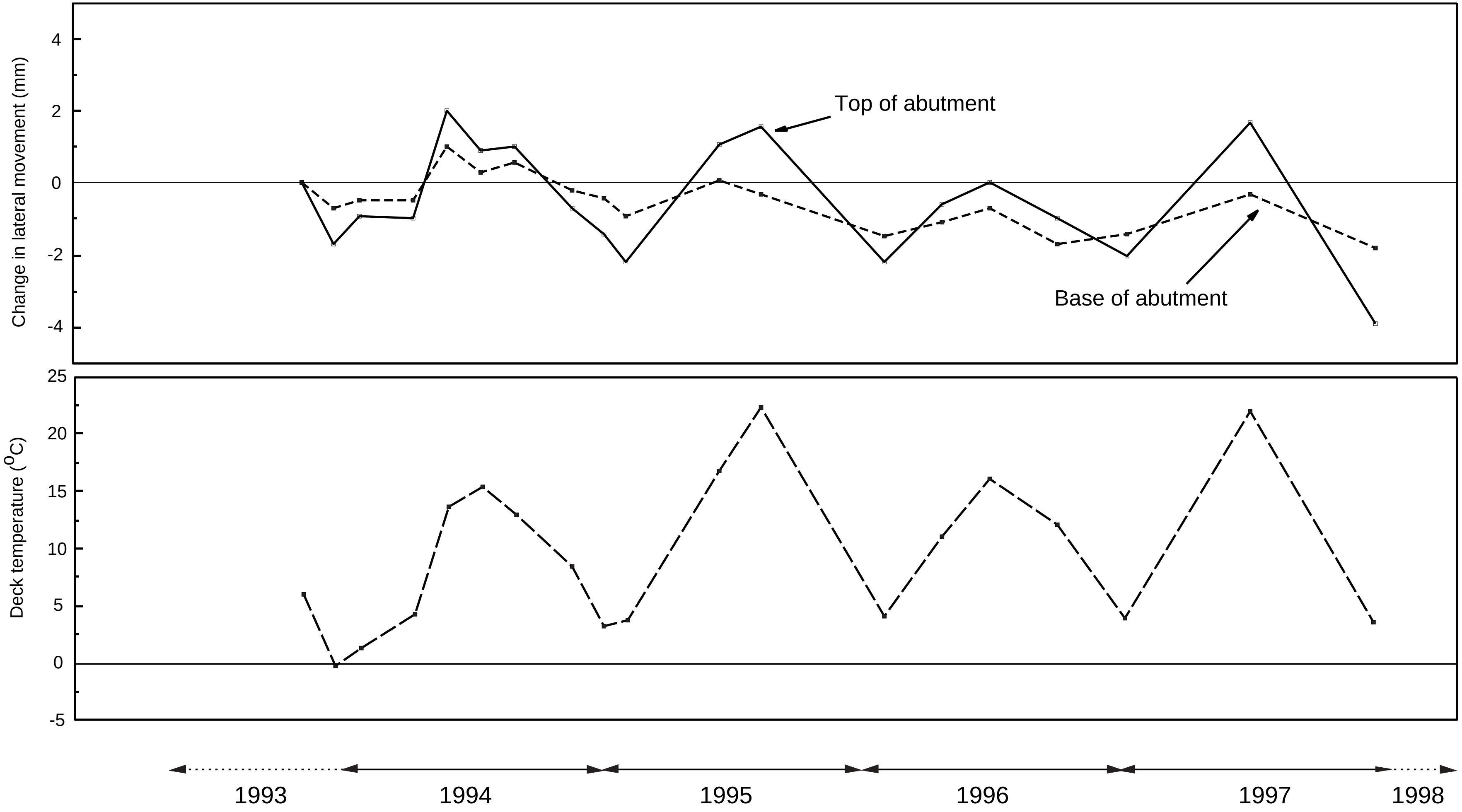

Figure 4 Variation of lateral movements of abutment and temperature

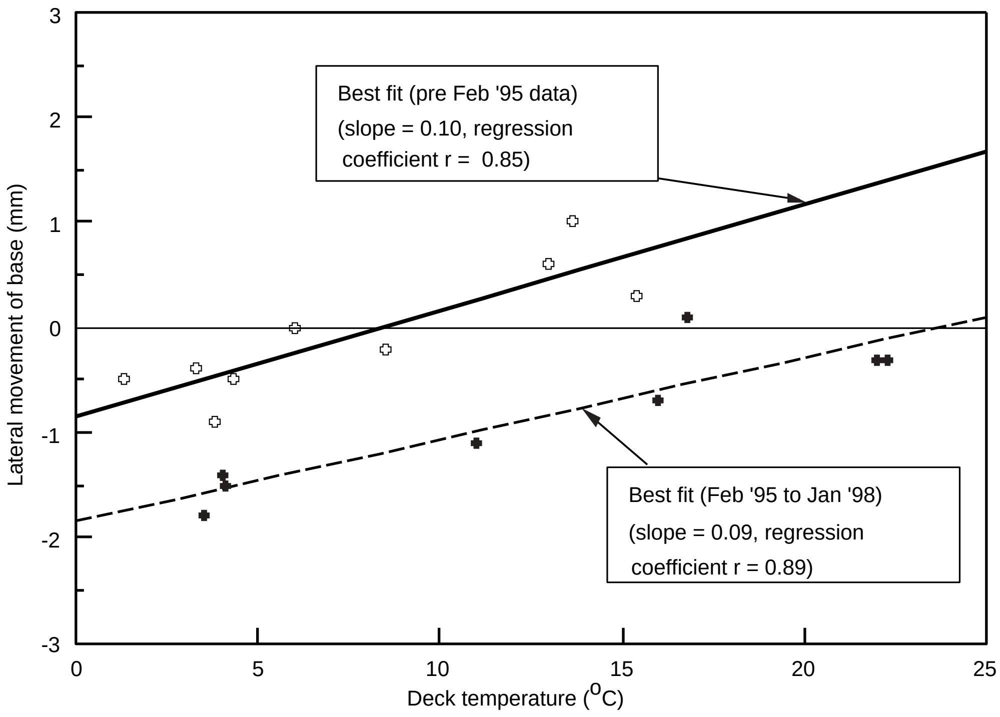

Figure 5 Variation of lateral base movement with deck temperature

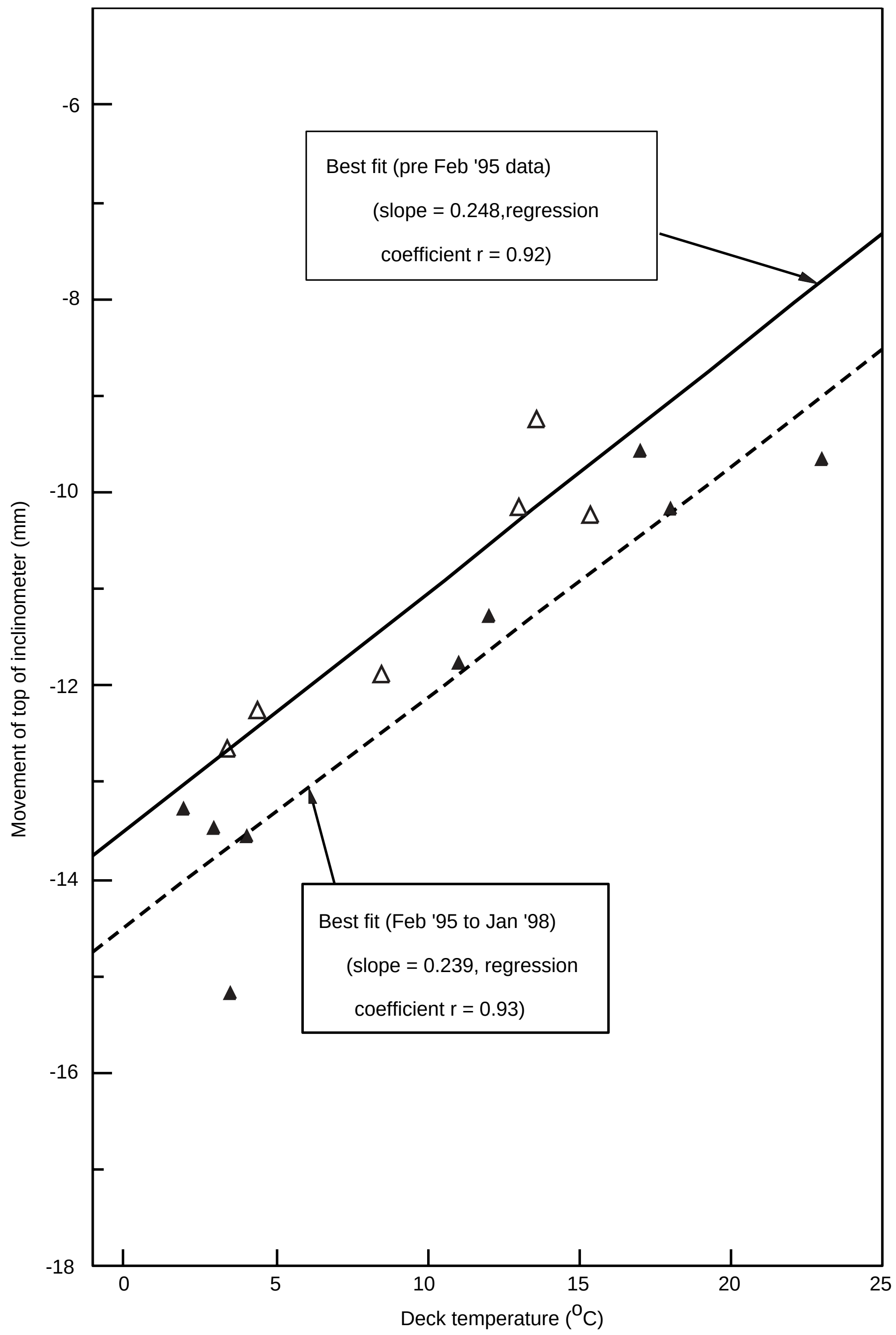

Figure 6 Change in lateral movement of top of inclinometer tube with deck temperature

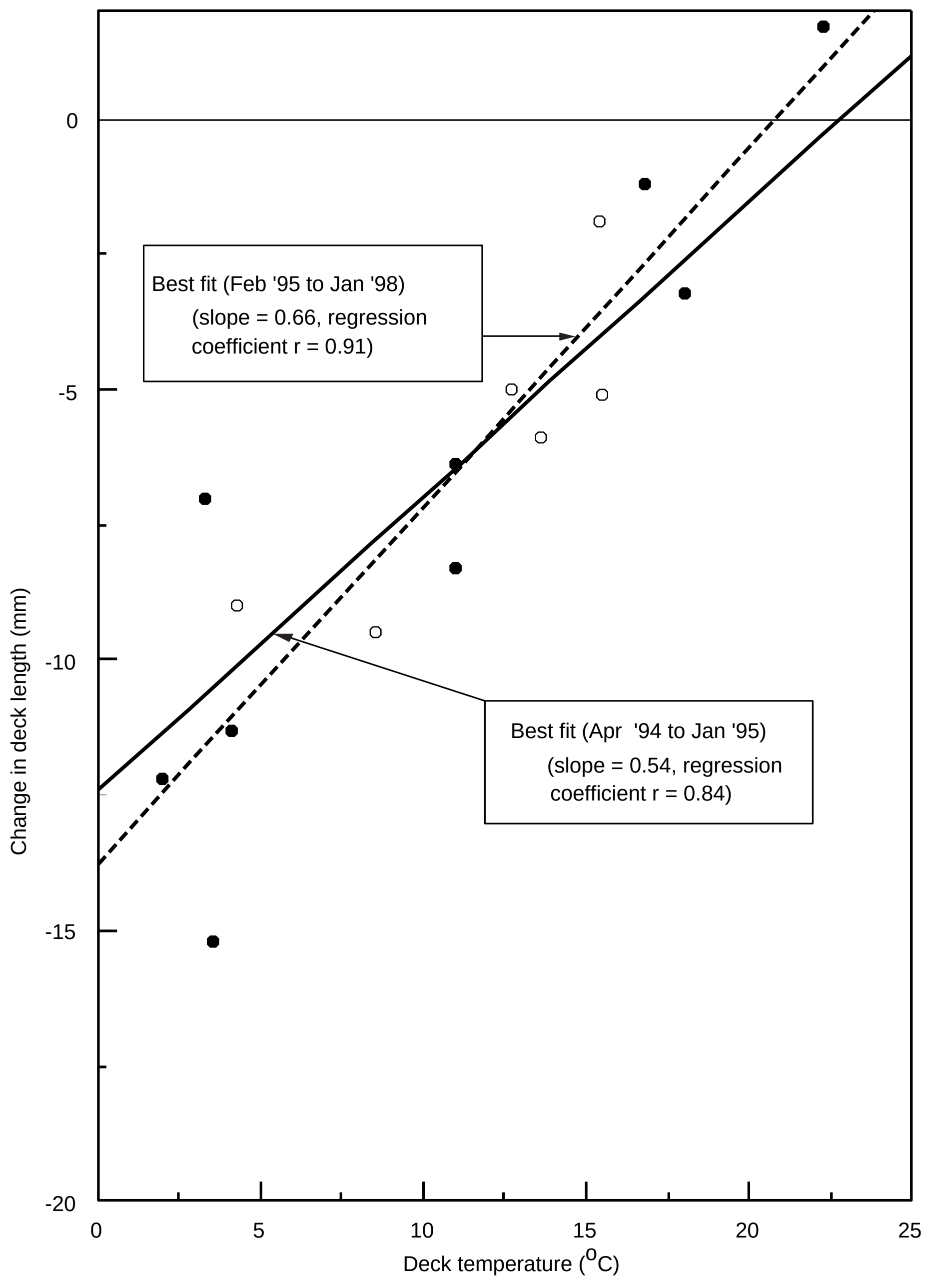

Figure 7 Change in deck length with temperature (length measured by Geomensor)

the deck. These coefficients are in reasonable agreement with the previously reported value of $9\times10^{-6}/^{o}C$ (Darley et al, 1996). The reduction in coefficient of expansion indicated by the inclinometer measurements taken after February 1995 was therefore not replicated by data on deck length changes, although the latter exhibit considerably more scatter than the inclinometer data. Such differences may also occur if the bridge behaviour is not symmetrical about its central pier.

Figure 8 shows the lateral movement of station G2 located above the central pier of the bridge (Figure 1) as measured by the Geomensor and also the mean deck temperature. The movement results are the average of the measurements from both reference pillars. The results indicate a small westerly movement of the centre of the bridge suggesting that the bridge behaviour is not symmetrical about the centre. The trend of westerly movements appears to be continuing and a total movement of about 5mm has occurred up to January 1998.

2.2 Changes in level of the bridge deck

Figure 9 shows changes in level measured along the deck on five arbitrary dates during the period from June 1995 to June 1997. The average deck temperatures are also shown, the maximum being 23°C and the minimum being 4°C. The levelling data were more erratic than those measured prior to 1995 (Darley et al, 1996) possibly because the east and west sections of the bridge deck no longer appear to behave symmetrically about the central pier. Levels on the ten survey points along the bridge deck showed the maximum change during the period from May 1996 and June 1997 was 2mm and no systematic trend with temperature was apparent. Levels taken in January 1998 showed no significant difference from those recorded in June 1997.

Precise levelling on the three settlement blocks in the fill below the run-on slab indicated that a small settlement of about 2mm had occurred between February 1995 and May 1996. A similar further movement occurred between May 1996 and June 1997 although no significant settlement was measured between June 1997 and January 1998. The total settlement from August 1993 (when the blocks were installed in the fill during construction) to January 1998 was about 7mm.

2.3 Lateral stresses acting on the abutment

2.3.1 Daily variation with temperature

Figures 10 and 11 show the variation in mean deck temperatures, together with the variation of lateral stress for pressure cells 1 and 6 (Figure 10) and cells 4 and 5 (Figure 11) from spring 1996 to January 1998. The outputs from all thermocouples and pressure cells were recorded every three hours during this period and the values shown are the daily averages in both cases.

The pattern of variation of lateral stress follows very closely that of the deck temperature. Temperatures were also measured at the pressure cell locations because the cells are fluid-filled and expected to have a small temperature sensitivity. However the variation of the cell temperatures was much less than those of the deck indicating that the changes in measured stress were due largely to variations in deck temperature, and hence deck length. In Figures 10 and 11, two dates have been identified when the deck and cell temperatures were virtually identical. On the second date in 1997 the measured lateral stresses were all higher than those recorded in 1996: these stress values are summarised in Table 1.

Table 1 Total lateral stress and cell temperatures for two dates of equal deck temperature

	Lateral stress(kPa)			*Cell temperature (°C)*	
Cell No	*17/6/96*	*31/5/97*	*% increase in stress*	*17/6/96*	*31/5/97*
1	27	28	6	16.5	15.3
2	22	25	14	15.4	14.1
4	23	26	10	14.5	13.5
5	35	36	2	13.7	13.5
6	86	106	23	12.8	13.0

Locations of the cells are shown in Figure 2.

The data in Table 1 show that the percentage increases in stress ranged from 2% to 23%. The largest increase was measured by cell 6 and two factors were considered to contribute to this. Firstly, the cell was situated on the toe of the abutment (Figure 2) where any movement was likely to cause a stress concentration. Secondly, the fill around cell 6 was placed and compacted as a working platform for abutment construction and was more densely compacted.

Figure 12 shows the variation in average deck temperature over a typical 24 hour period. The deck temperature shows a minimum value at about 9am (GMT) rising over the following nine hours to reach a peak at about 6pm (GMT). Movement measurements at this site required a lane closure and were always made during the period 8am to 1pm which coincided with a period of relatively stable temperatures.

A typical daily cycle of lateral stress with deck temperature as measured by the top cell 1 is shown in Figure 13. It is evident that a small hysteresis effect of less than 1kPa occurred between the expansion and contraction phase.

2.3.2 Magnitude of the stresses

An assessment of the range of soil lateral stresses developed on the abutment is given in Figure 14. The values have, on this occasion, been corrected for thermal effects acting on the cells. The corrections applied to the shallower cells were generally more significant than those applied to the deeper cells because the former were subjected to larger temperature variations.

In Figure 14 the stresses measured in January 1995, November 1996 and January 1998 represent the lowest recorded stresses whilst those for August 1995, July 1996 and August 1997 represent the highest values. The stresses recorded in August 1997 were slightly higher than for 1995 and 1996 for very similar temperature conditions. Also shown in Figure 14 for comparison purposes are the calculated lateral stresses for K values (ratios of horizontal to vertical effective stress) of 1 and 2. The maximum

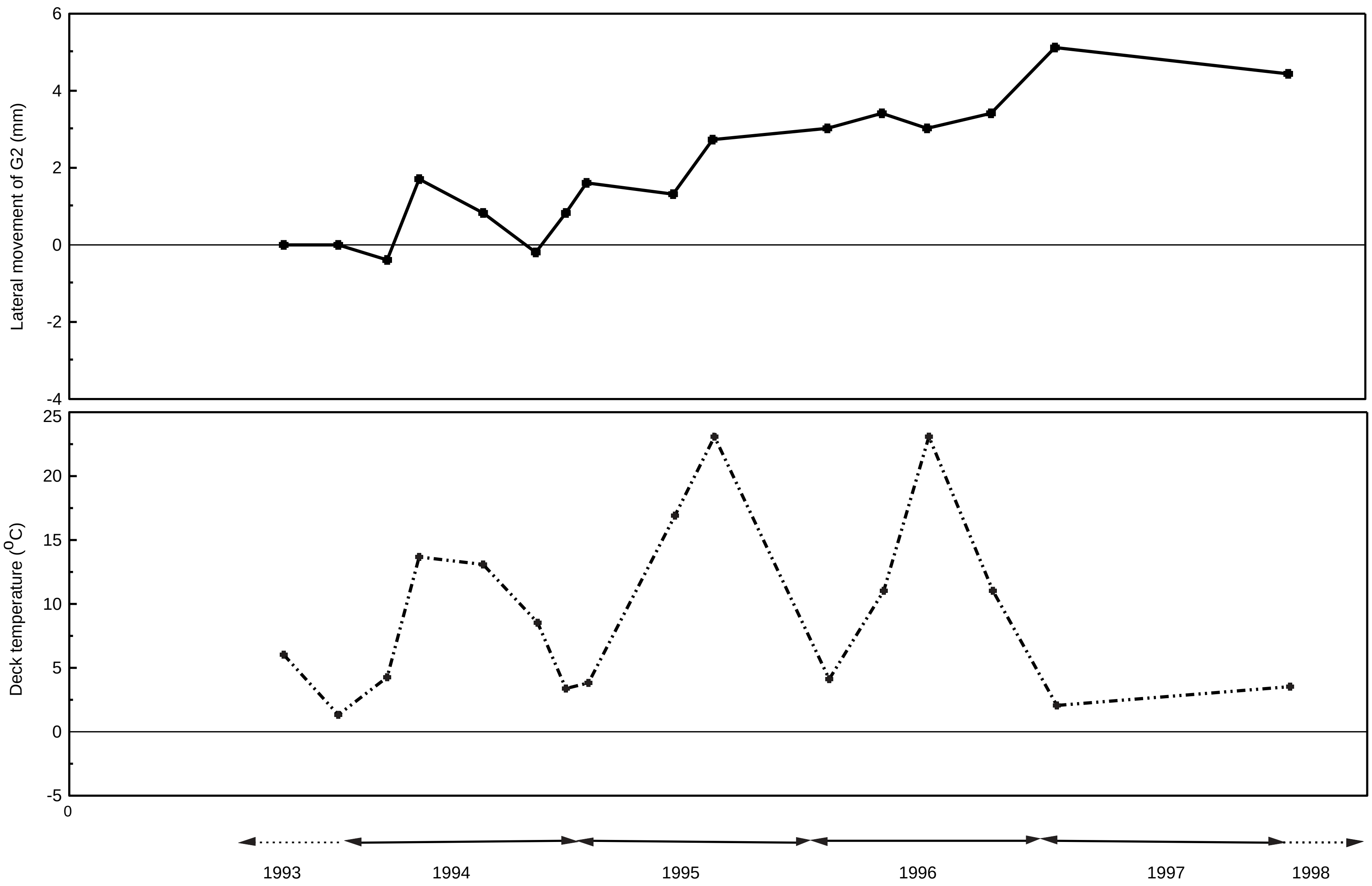

Figure 8 Movement of top of central pier and variation of deck temperture

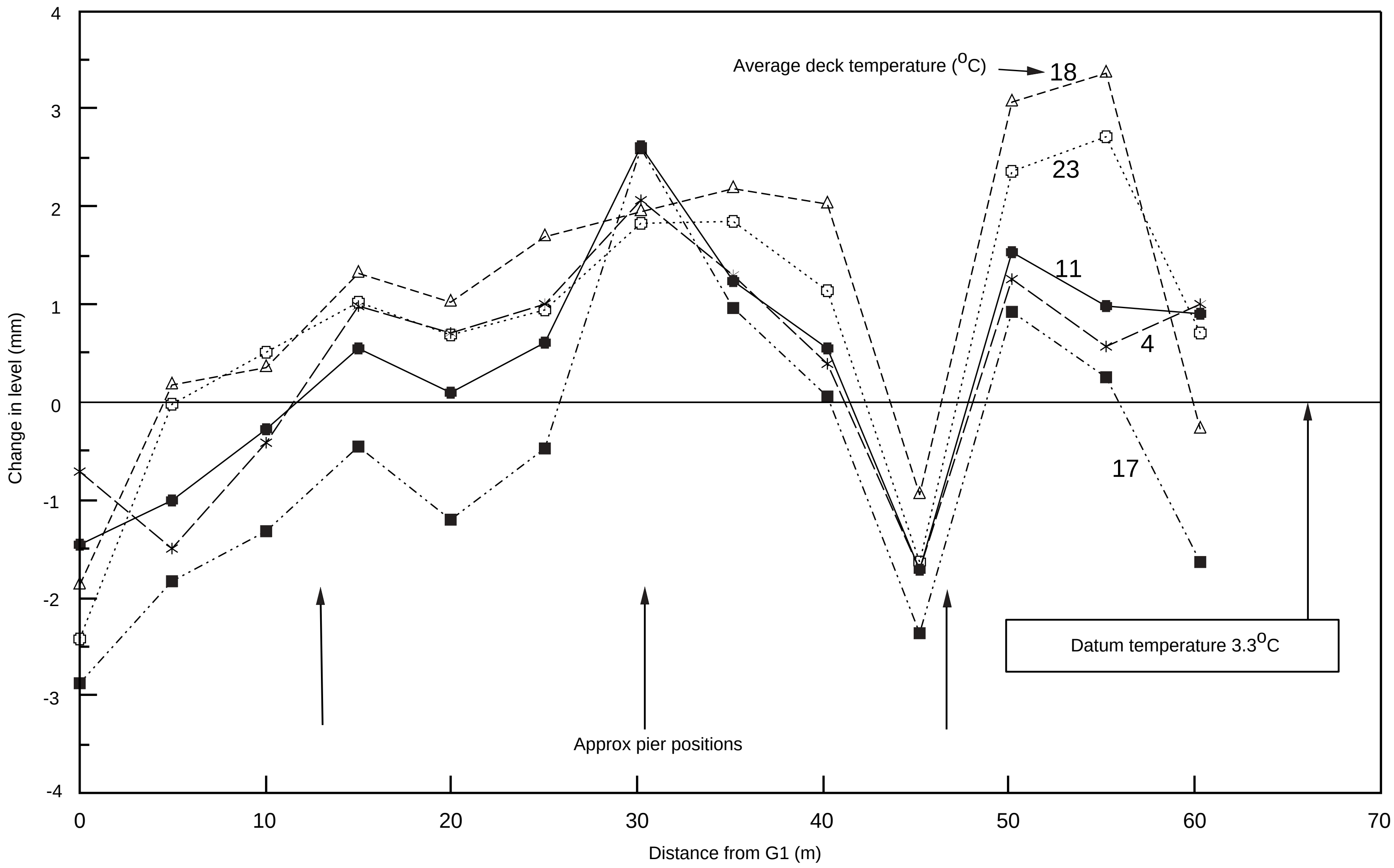

Figure 9 Change in level of bridge deck

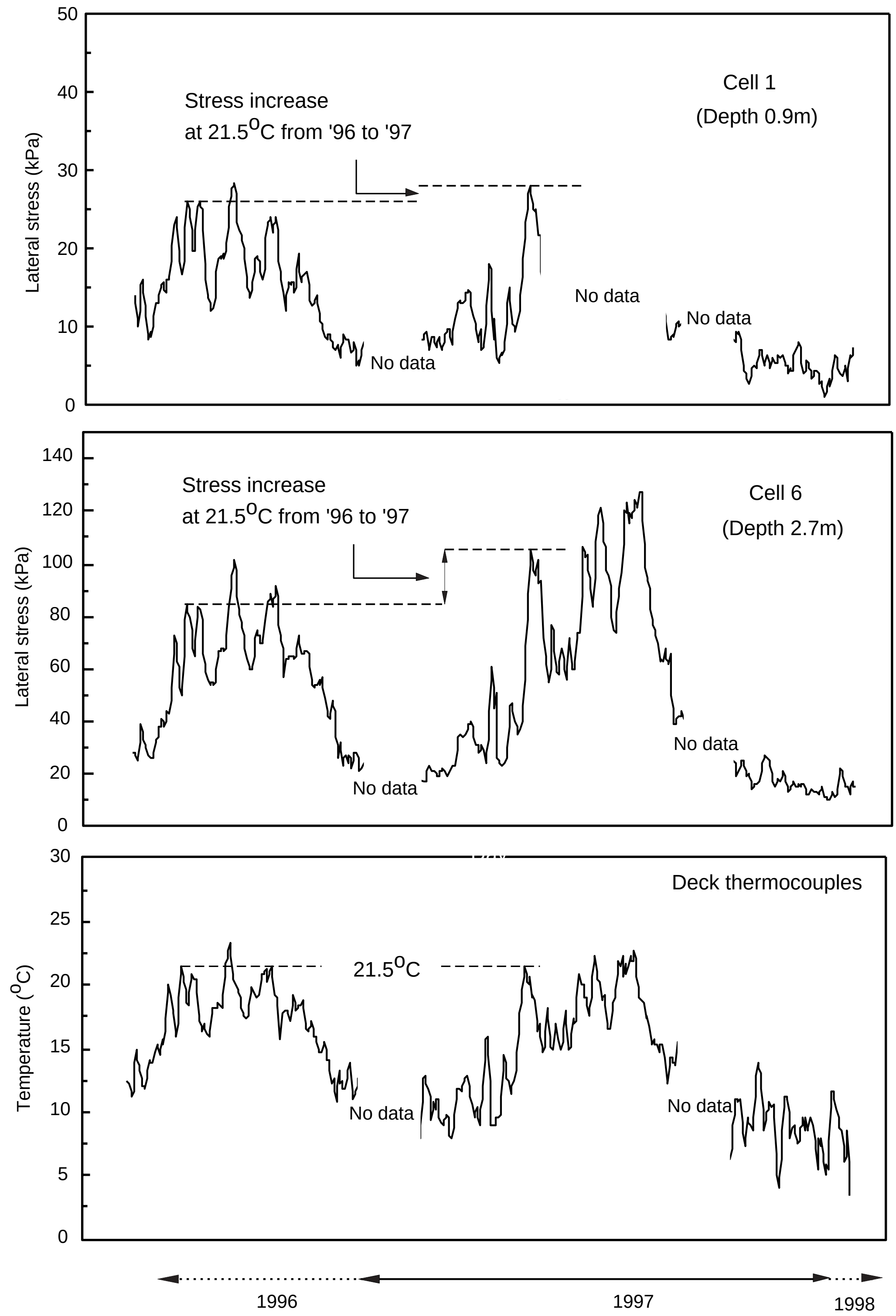

Figure 10 Variation of lateral stress on abutment and temperature (cells 1 and 6)

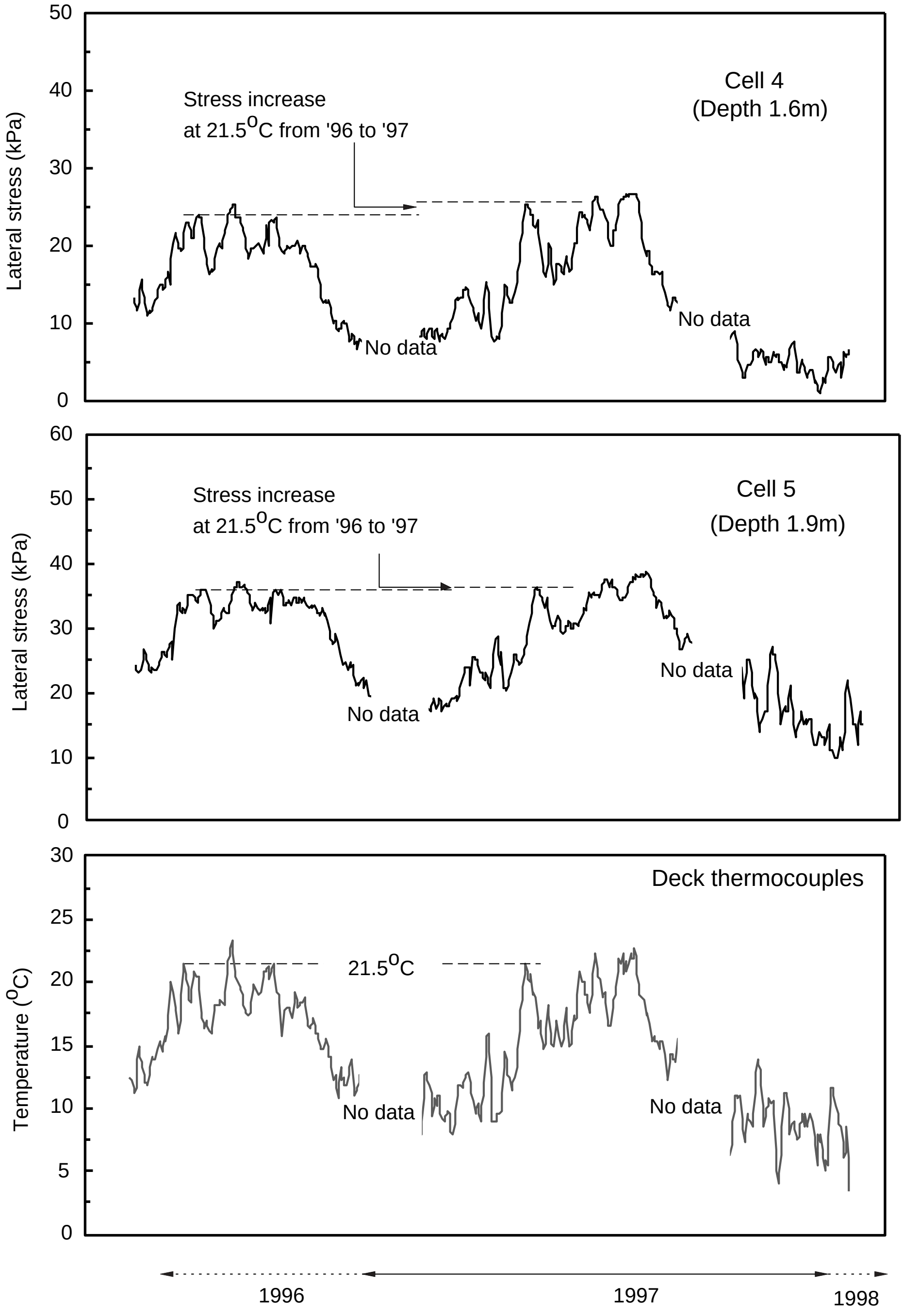

Figure 11 Variation of lateral stress on abutment and temperature (cells 4 and 5)

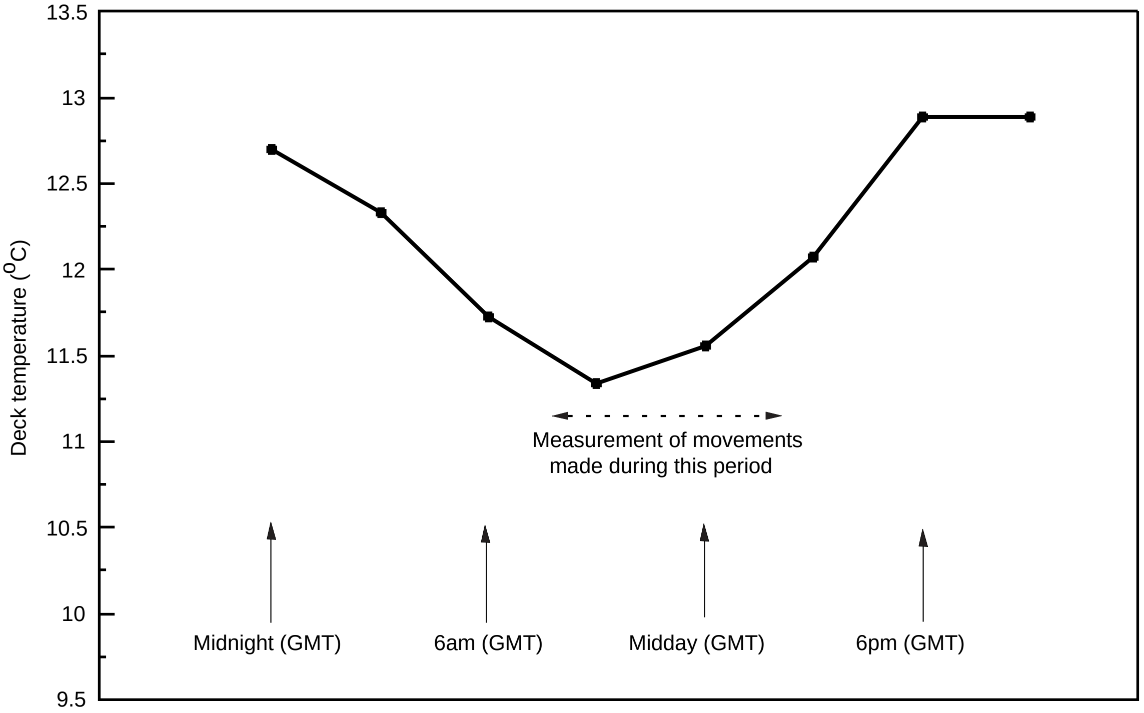

Figure 12 Mean deck temperature over typical 24 hour period

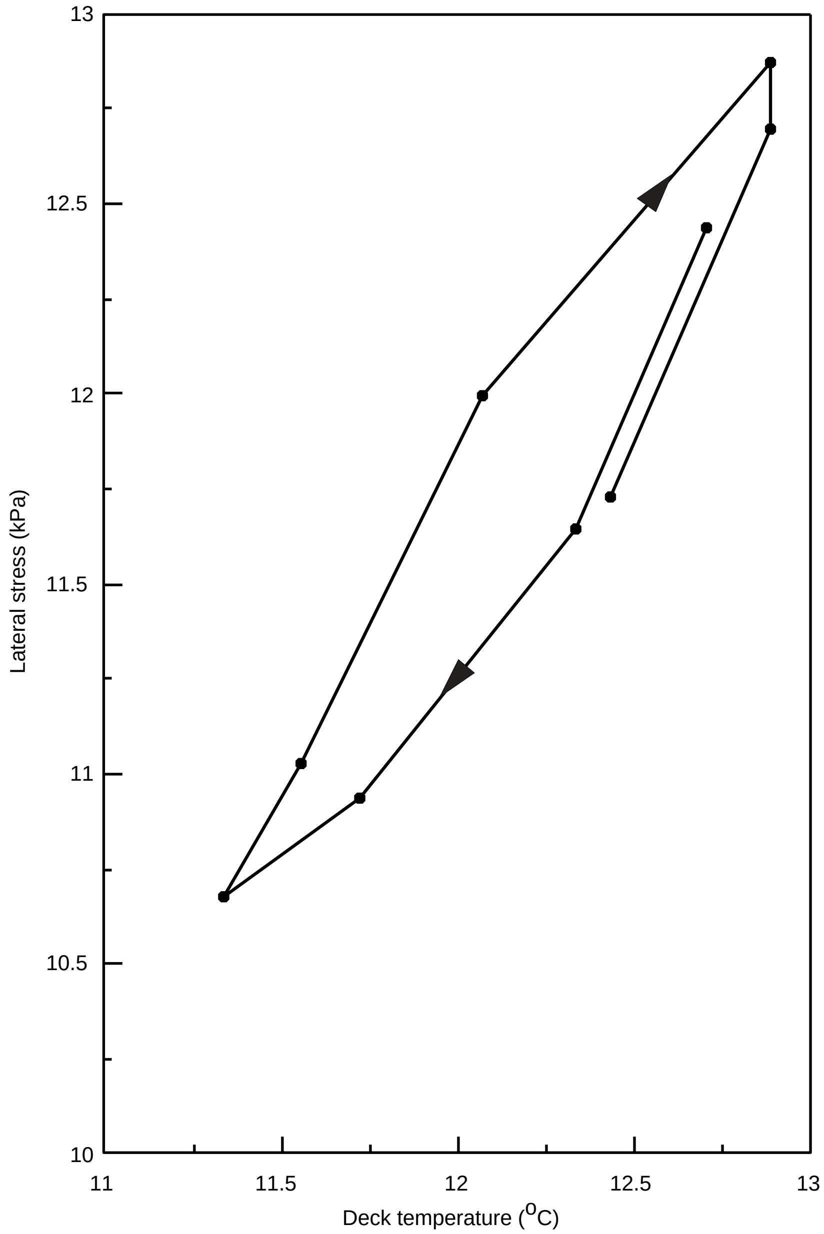

Figure 13 Variation of lateral stress at cell 1 with deck temperature over 24 hours

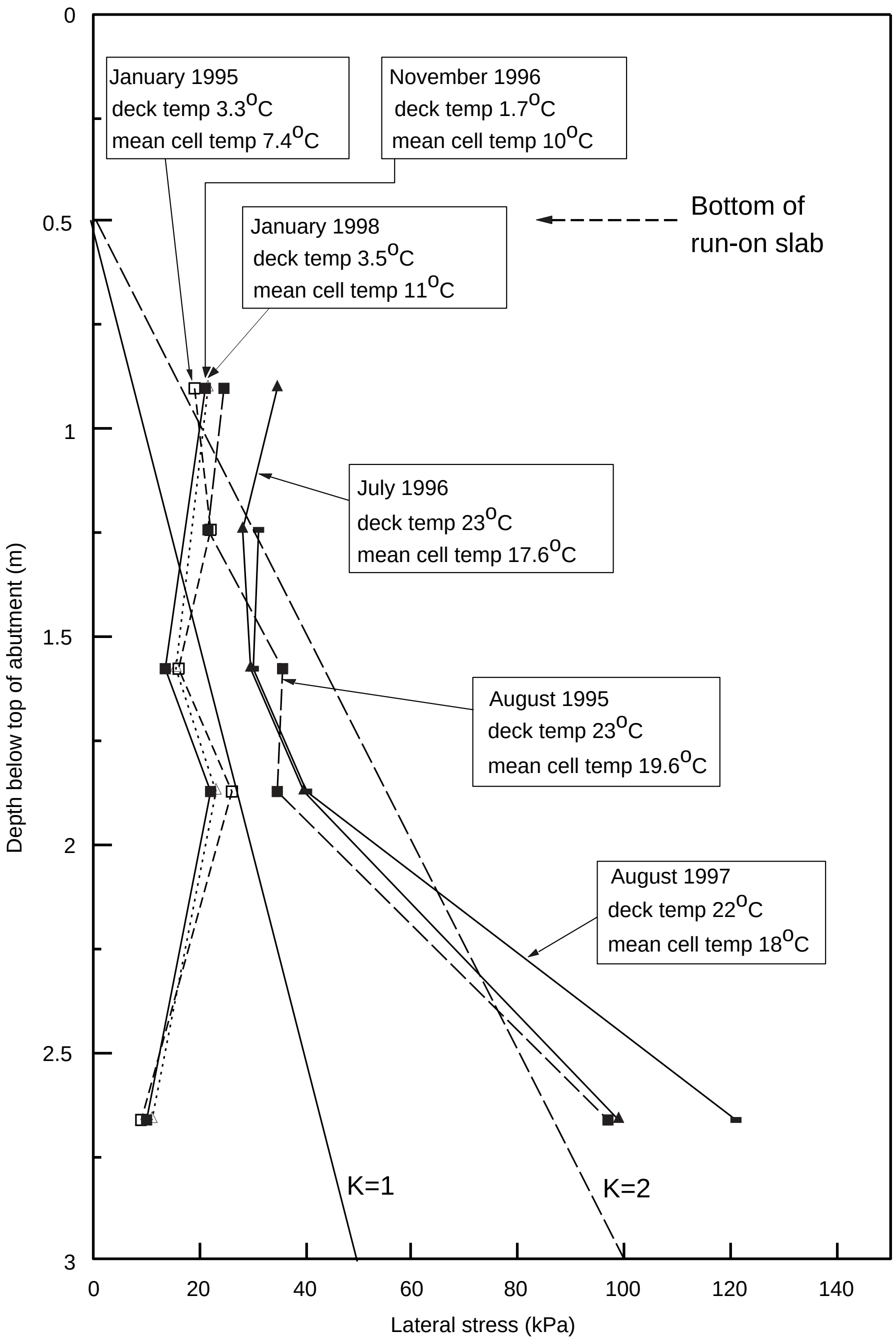

Figure 14 Range of lateral stresses (corrected for temperature effects) acting on the abutment

stresses were without exception higher than a K value of 1 and, in the case of both the top and bottom cell, just exceeded a K of 2. Stresses were much larger than the average K values of 0.85 reported by Darley et al (1996) for the readings taken at the previously highest available deck temperature of 15.5°C.

3 Discussion

Measurements of lateral movement showed that thermal expansion of the deck produced movement of the shallow abutment of the 60m long integral bridge on the M74. The data indicated that a combination of tilting and translation of the reinforced concrete abutment was taking place. Translation of the base of the abutment was probably accommodated by a combination of sliding and deformation of the soil foundation, although it was not possible to quantify the relative proportions of the movement due to each mechanism.

Regression analyses of the lateral movement of the top of the abutment established by inclinometer gave values of 0.248mm/°C and 0.239mm/°C for data retrieved before and after February 1995. Equivalent coefficients of thermal expansion of the deck of 8.2×10^{-6}/°C and 7.9×10^{-6}/°C respectively are obtained on dividing by the bridge half-span. On the basis of a comparison with the value of 9.2×10^{-6}/°C reported by Darley et al (1996) during the construction period, a small decrease in the apparent coefficient may be occurring with time which would be consistent with densification of the backfill and an increased resistance to lateral movement caused by the cyclic loading. However the following factors could contribute to producing this effect:

- the sensitivity of the calculations to small measured movements of less than 1mm
- the assumption of base fixity of the inclinometer tube
- any asymmetrical behaviour of the bridge about its central pier.

Separate investigation of the overall change in deck length using the Geomensor system showed that the coefficient of thermal expansion was 9×10^{-6}, 10.9×10^{-6} and 9×10^{-6}/°C for the construction period, the pre February 1995 and post February 1995 periods respectively. The small reduction in coefficient of expansion with time indicated by using the abutment inclinometer results and the bridge half span was not therefore replicated by the data on overall deck length changes. This anomaly was found to be a consequence of a small westerly movement of the central pier. Although this pier movement could have resulted from an increased lateral resistance of the backfill at the instrumented eastern abutment, similar behaviour at the western abutment would be expected to have counterbalanced this.

It was therefore concluded that, within the accuracy of measurement, the deck was continuing to move with a thermal expansion coefficient of about 9×10^{-6}/°C. This value was consistent with that expected for the concrete which used a crushed gravel aggregate that was largely composed of geologically transported and weathered volcanic rock (Blundell et al, 1976; Bonnell et al, 1951).

During July 1995, August 1996, and August 1997 the highest recorded deck temperatures of 22°C to 23°C caused large increases in measured lateral stress to values which were without exception higher than a K value of 1 (Figure 14). In the case of the top cell and the bottom cell (installed on the abutment toe), the measured stresses exceeded a K value of 2. The high value at the top of the abutment was not unexpected as this is where the maximum lateral movement due to cyclic loading will occur. At the toe of the abutment, stress concentrations are likely to occur particularly as the fill in this area was placed and compacted as a working platform for abutment construction and was more densely compacted.

After many annual and diurnal cycles of expansion and contraction, a build up in lateral stress levels on the remaining cells is possible as ‘strain ratcheting‘ occurs accompanied by significant densification of the fill over the abutment height. Springman et al (1995) carried out centrifuge and analytical studies on spread-base abutments and found that, irrespective of the initial density of the backfill, densification occurred up to a limiting value. A comparison of lateral stresses for two days when deck and cell temperatures were effectively the same (Figures 10 and 11) and hence no cell temperature correction was required showed that between June 1996 and May 1997 an increase in stress occurred on each cell (Table 1). This provides some indication that the density and stiffness of the backfill may have increased over the yearly cycle of expansion and contraction. Monitoring of several further annual cycles will be required to ascertain whether or not the lateral stresses continue to increase.

The current recommendation in BA42 (DMRB 1.3) for a shallow bank seat abutment is the use of full passive force for the abutment design and this force can usually be readily accommodated within the design. For the ϕ' of 41° measured for the backfill at this site, this would correspond to K_p values of 4.8 and 10 assuming an unfactored ϕ' value and wall friction angles of zero and $\phi'/2$ respectively. The results of this study have demonstrated that for bridge deck temperatures of up to 23°C, K values exceeding 2 can be produced. Given that maximum effective bridge temperatures of about 33°C could be reached in Glasgow for a 120 year return period (BD37, DMRB 1.3), even higher K values might be anticipated. Further backfill stress measurements are required for an integral bridge which has been in-service for more than a decade or better quantification of wall friction against integral abutments, to enable further refinement of the current recommendations of BA42.

4 Conclusions

The seasonal effects on a shallow integral abutment of thermal expansion and contraction for a 60m long bridge deck at Glasgow have been reported during its construction and first year in service after opening of the bridge in April 1994 (Darley et al, 1996). This update describes the results of further monitoring until January 1998.

1 Movement data indicated that a combination of tilting and translation of the reinforced concrete abutment was taking place. Translation of the base of the abutment was probably accommodated by a combination of sliding and deformation of the soil foundation, although it was not possible to quantify the relative proportions of the movement due to each mechanism.

2 Measurements between the abutments of the bridge showed that the deck length had continued to change with temperature with a coefficient of thermal expansion of about $9 \times 10^{-6}/^{o}C$. This value was consistent with that expected for the deck concrete which used a crushed gravel aggregate that was largely composed of geologically transported and weathered volcanic rock.

3 Measurements of movement of the eastern abutment were found to be less than expected on the basis of expansion of the bridge half-span and showed slight evidence of a decrease with time. Initially this was ascribed to densification of the backfill producing an increasing lateral restraint to movement: however further investigation showed that it could also be a consequence of a small westerly movement of the central pier.

4 The bridge temperatures of up to $23^{0}C$ recorded in the summers of 1995, 1996 and 1997 gave rise to significantly increased lateral stresses on the retained face of the abutment. These stresses were without exception higher than a K value of 1 and, in the case of the top cell and the bottom cell (installed on the abutment toe), the measured stresses exceeded a K value of 2. The high value at the top of the abutment was not unexpected as this is where the maximum lateral movement due to cyclic loading will occur. At the toe of the abutment, stress concentration occurred and this was particularly noticeable as the fill in this area was used as a working platform for abutment construction and had become densely compacted.

5 Lateral stress measurements on two dates when cell and deck temperatures were effectively the same indicated an increase in lateral stress between June 1996 and May 1997. This provides some indication that the density and stiffness of the backfill may have increased over the yearly cycle of expansion and contraction. Monitoring of further annual cycles will be needed to ascertain whether ‘strain ratcheting‘ is occurring and whether the stresses will continue to increase.

6 The changes in level of the bridge deck with temperature were more erratic than previously observed, but generally remained less than 2mm. Overall settlement of the fill beneath the run-on slab was 7mm from the start of construction until January 1998, an increase of 4mm since February 1995.

5 Acknowledgements

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BA 42 *The design of integral bridges* (DMRB 1.3)
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Springman S M, Norrish A R M and Ng C W W (1996). *Cyclic loading of sand behind integral bridge abutments.* TRL Report TRL146. Transport Research Laboratory, Crowthorne.

Abstract

Instrumentation was installed during the construction of a bridge of about 60m span with a continuous deck and shallow integral abutments at Carmyle Avenue, Glasgow. Abutment performance during its construction and first year in service have been reported previously. This update describes results of the monitoring from February 1995 to January 1998. Seasonal thermal expansion of the deck caused cyclic movements of the abutments and the magnitude of these movements was measured together with the earth pressure developed in the granular backfill behind the abutment.

Related publications

TRL178 *Seasonal thermal effects on the shallow abutment of an integral bridge in Glasgow* by P Darley, D R Carder and G H Alderman. 1996 (price £20, code E)

TRL165 *Measurement of thermal cyclic movements on two portal frame bridges on the M1* by P Darley and G H Alderman. 1995 (price £20, code E)

TRL146 *Cyclic loading of sand behind integral bridge abutments* by S M Springman, A R M Norrish and C W W Ng. 1996 (price £75, code T)

PR52 *A literature review of the geotechnical aspects of integral bridge abutments* by G B Card and D R Carder. 1993 (price £35, code J)

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