MECHANICAL STRAIN GAUGE MEASUREMENTS AT TE MARAU

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ABSTRACT

In 1981 an array of five steel rods linking four monument was installed across the trace of the Wellington Fault, at the site of the Te Marau water storage project. This array was instrumented with electronic displacement transducers and data loggers to serve as a horizontal strainmeter. Corresponding measurements have been made from time to time using a Whittemore mechanical strain gauge. Though these measurements are consistent with a model of right lateral shear deformation at an average rate of $(5 \pm 2) \times 10^{-6}$/yr (engineering units) since 1982, some or all of this estimate may be due to flexure of the rods; it may therefore be considered as an upper limit to deformation at the site. Verification by precise surveying methods may be possible if there is a sufficiently broad zone of deformation.

INTRODUCTION

The Wellington fault has been described by Lensen [1958]; its strike near Te Marua is about 060° and, citing Berryman (in prep.), Brown and Wood [1983] give an average right lateral offset rate of 7.4 mm/yr over the last 140,000 years. The strainmeter at the site of the Te Marua water storage project was installed in 1981 to measure deformation about the fault, and is described by Brown and Wood [1983]. It was assembled in a 10 m deep trench, now backfilled, and consists of an approximately horizontal array of five stainless steel rods; two of these cross the trace of the Wellington fault diagonally, two are parallel to it, and the fifth is nearly perpendicular to it (Figure 1). The rods have lengths from 5 m to 10 m. One end of each rod is anchored to rock and the displacement of the other end can be measured relative to an engraved moument. Access is by two manholes referred to as north manhole (NM) and south manhole (SM); the anchored ends are referred to as north anchor (NA) and south anchor (SA). These abbreviations are used for naming the rods. Electronic displacement and temperature transducers, and data loggers, were installed as the principal data acquisition system, but punched holes in the rods and monuments were also provided to permit subsidiary measurements with a mechanical strain gauge. While some of the electronically logged displacements have been reported [Brown and Wood 1983], there have been problems with continuity and calibration of the outputs. The following discussion is limited to the mechanical strain gauge results.

STRAIN GAUGE MEASUREMENTS

The gap length between the punched hole at one end of each rod and a corresponding hole aligned with the rod on the monument has been measured 13 times between March 1982 and September 1985, with a Whittemore six-inch mechanical strain gauge. The set of five measurements taken on each occasion will be called a survey. A gauge measurement consists of the difference between a mean dial reading with the gauge set in drill holes in an invar standard bar. This procedure eliminates any change in the zero error of the gauge. Although the dial is graduated to 0.0001 inch intervals (estimation 0.00002 inch) experience shows that measurements are repeatable only to about 0.001 inch or 25 μm. Some expertise is required to accomplish this repeatability. The mean dial readings are means of individual readings taken with the gauge held in each of the two possible orientations. On several occasions the difference between these individual readings was quite large (over 0.00200 inch or 50 μm). When repetitions were not made in these circumstances, the measurements are of doubtful reliability, and 8 such measurements have been rejected from the data set. The problem is attributed to the age and condition of the gauge and the poor quality of the punched holes used in this experiment. Nevertheless, a measurement of linear strain over a 5 m distance should be accurate to 5×10^{-6}. Measurements in the five different orientations over the three year time period may permit estimation of areal strain rate components to an accuracy approaching 1×10^{-6}/yr, if the strain is spatially uniform and at a constant rate throughout the time period.

Figure 2 shows the gauge measurements for each rod. The ordinate origins depend in each case on the original gap lengths and are of no significance, but the similar trend of each trace indicates that the measurements on each occasion show consistency amongst themselves, and that there is a common, possibly systematic, behaviour of each of the five measured gaps. This could be attributed to areal dilatations at the site, but other more obvious effects

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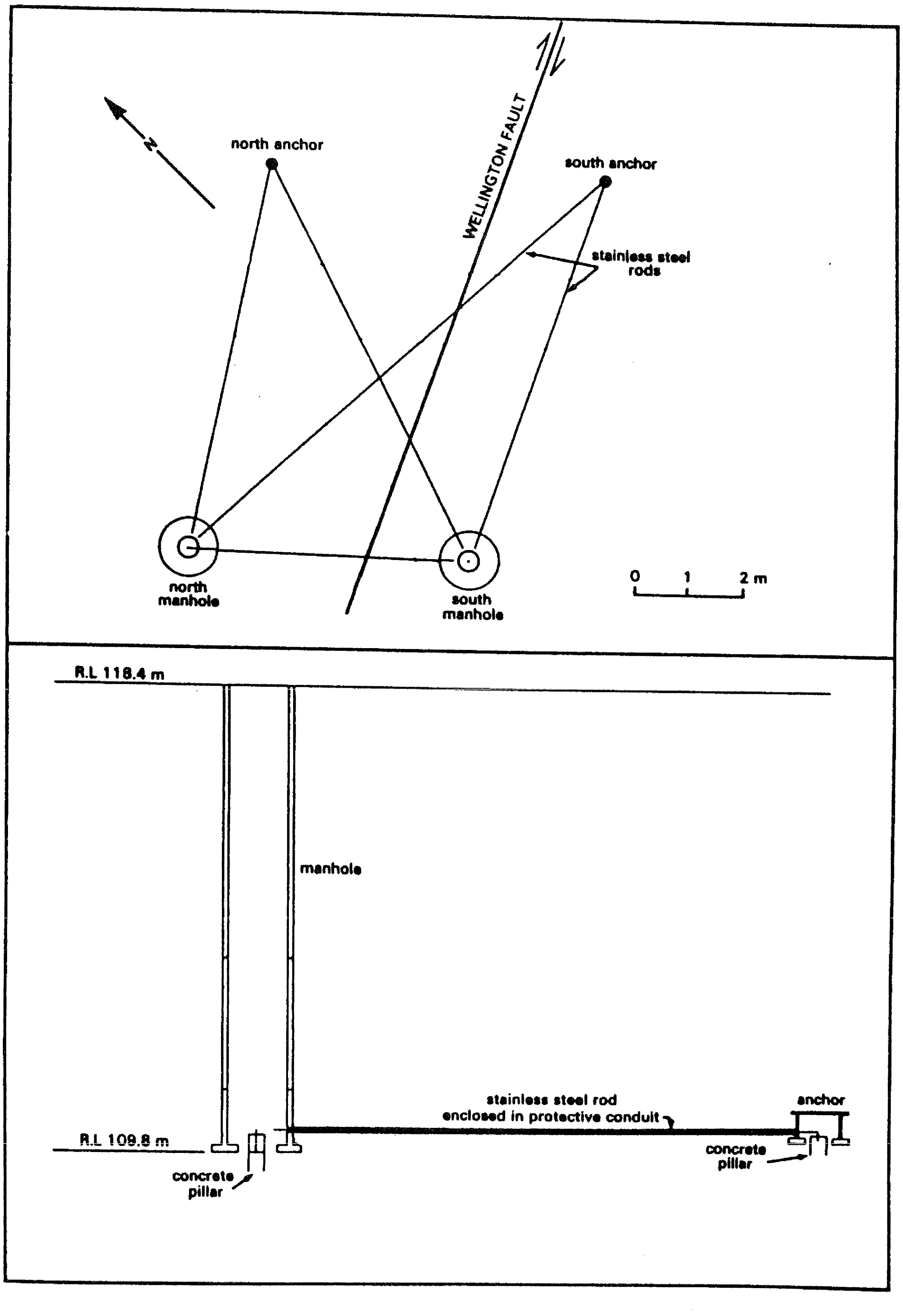


FIGURE 1 : PLAN AND SECTION OF STRAINMETER INSTALLATION AT TE MARUA (AFTER BROWN AND WOOD (1983)), AND ITS RELATIONSHIP TO THE TRACE OF THE WELLINGTON FAULT.

such as temperature variations, changes in the gauge or invar standard, and flexure of the rods must be considered.

DATA ANALYSIS

The electronically logged temperatures of the rods varied between 9°C and 13°C. This difference would induce a thermal change in length of about 600 μm for the longest rod, i.e. some 25 times the resolution of the gauge. It is therefore crucial that account be taken of temperature effects; it is recognised that access to the rod ends, via the manholes, may itself affect the temperature at the rod end at the time of a mechanical measurement. The original design of electronically logged transducer outputs circumvents this problem.

The number and positions of the monuments with respect to the fault trace do not allow any differentiation between transcurrent slip of the fault itself and shear deformation parallel to its strike. In the small area this array samples, we feel such a distinction is not relevant from a regional point of view, and strain components will be estimated, rather than relative displacements, to take advantage of measurement redundancy. Temperature measurements are not available to correct all the measurements for thermal changes of rod lengths. We therefore estimate parameters of the model:

$$g_{rs} = g_r^\circ + d_s L_r + \dot{\gamma}_1 t_{s1} L_r \cos 2\theta_r + \dot{\gamma}_2 t_{s1} L_r \sin 2\theta_r + \varepsilon_{rs} \qquad (1)$$

where r = 1, --, 5; s = 1, --, --, 13 except as noted.

g_{rs} is the gauge measurement for rod r in survey s;

g_r° is the ideal initial measurement for rod r, in the absence of random or modelling errors, and must be estimated;

d_s is the apparent linear dilatation compared to the first survey for each subsequent survey s (s > 1); these are to be estimated and are discussed in detail below;

$\dot{\gamma}_i$ (i = 1,2) are the two (tensor) strain rate components, assumed constant in time, which describe uniform shear strain; they are to be estimated;

t_{s1} is the time of survey s after the first (s > 1);

L_r is the length of rod r;

θ_r is the azimuth of rod r;

ε_{rs} is the random error for rod r in survey s; errors are assumed to have a normal distribution with mean zero, and a standard deviation which will be estimated from the residuals.

For 13 surveys of 5 rods there are thus 65 observations to determine 19 parameters; there would therefore be 46 degrees of freedom, but the 8 dubious measurements have been rejected. In general, for S surveys there are potentially 4S-6 degrees of freedom.

The apparent dilatation d_s for each survey after the first may have a contribution from a real areal dilatation Δ_s, as well as from thermal expansion or contraction of the steel rods, which we assume to have all the same temperature. Therefore

$$d_s = \frac{1}{2}\Delta_s - \alpha(T_s - T_1) \quad (s > 1) \qquad (2)$$

where α is the coefficient of thermal expansion for the rods (15.9×10^{-6}/C°) and T_s is the rod temperature at the time of survey s.

After estimating the apparent dilatations, it would be of some interest to compare them with the recorded temperature where this is available, in order to substantiate this method of using the array itself as a thermometer. At present there are insufficient temperature data to do this.

Since the invar standard is occasionally subjected to inertial damage (by being dropped, etc.) in the field, and has never been calibrated against one maintained under laboratory conditions, it may be of interest to extend the model to allow for any discrete change the standard may suffer. This may be possible by adding a term f_s ($s \geq 2$) to the r.h.s. of equation (1), and estimating these as fiducial corrections independent of rod length. This has yet to be done.

The systematic and important effects of rod flexure are discussed after the results of application of model (1). It will be seen that these effects depend inversely upon rod length. Though perhaps of academic concern at present, an array of equally long rods (as in an asterisk formation, coupled at their crossing) would permit the fiducial corrections and flexure contributions to be incorporated in the apparent dilations without reducing the number of degrees of freedom in fitting the model.

STRAIN ESTIMATES

The estimated apparent dilations are shown in Figure 3. The range, if due to temperature effects alone, corresponds to a temperature variation range of some 2°C, well within that indicated by the electronically logged temperature transducers.

The results for $\dot{\gamma}_1$ and $\dot{\gamma}_2$ correspond to a maximum engineering shear rate of $(6.0 \pm 1.8) \times 10^{-6}$/yr right laterally at an azimuth of 076 ± 010°. This can be resolved into a right lateral shear rate of $(5.0 \pm 1.8) \times 10^{-6}$/yr parallel to the strike, 060°, of the predominantly transcurrent Wellington fault at the locality of the strain meter [Lensen 1958], together with orthogonal extension-contraction components whose magnitude and interpretation cannot be properly discussed without knowledge of the real dilatations Δ_s. (If the 8 dubious measurements are not rejected, the results are similar, but the shear rate is somewhat greater).

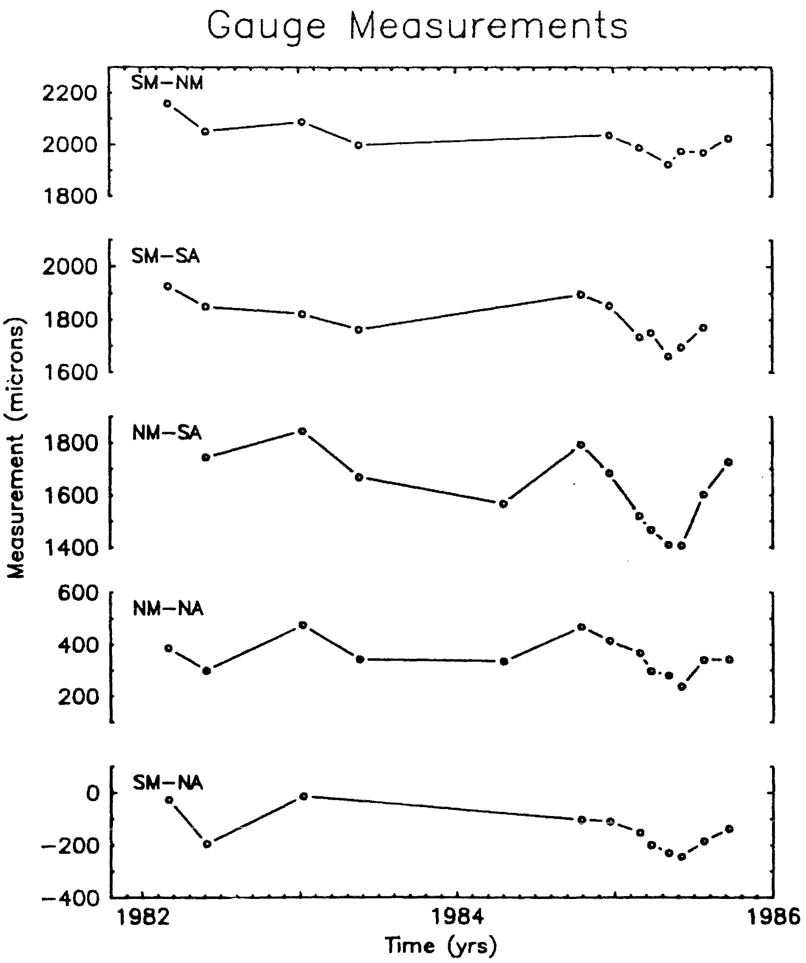


FIGURE 2 : MECHANICAL STRAIN GAUGE MEASUREMENTS OF THE GAP BETWEEN THE END OF EACH ROD AND THE CORRESPONDING MONUMENT.

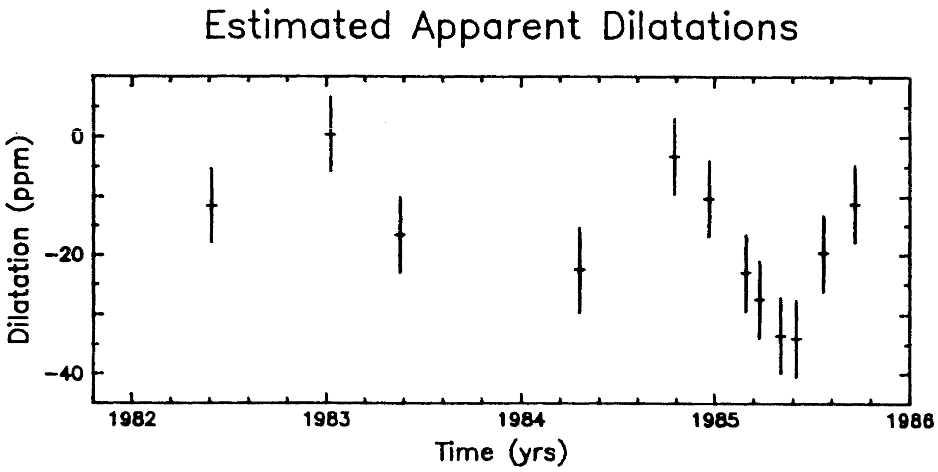


FIGURE 3 : THE ESTIMATED APPARENT DILATATIONS, AS DEFINED IN THE TEXT.

A representation of the measurements in terms of the model is shown in Figure 4; for each rod the contributions to the gauge measurement of the estimated apparent dilatation, d_s, and ideal initial measurement, g_r°, have been subtracted, leaving shear strain and random error contributions. The plotted straight lines show the trend expected for the estimated shear strain alone. These lines are determined by the two components of shear strain and the rod orientation; they are not independent fits to the plotted points. Apart from showing the measurements with apparent dilatations removed, these plots show the scatter of measurements about the model expectation. The error bars show the estimate of the standard deviation of the quantities ε_{rs}, 35 µm, which, as expected, is greater than, but comparable to, the experienced repeatability of measurements. It does appear that monthly measurements are desirable. A possible interpretation of details of these plots in terms of rod flexure will be treated in the following section.

ROD FLEXURE

The effects of rod flexure are important and deserve some detailed discussion. Other systematic effects, as we have seen, can be incorporated in the model much more easily.

Though each rod lies inside a galvanised iron pipe, of diameter 65 mm, they can and have been observed to sag. Within a few days of installation of the strainmeter, in October 1981, it was noted that the sag of two pipes, NM-NA and SM-NA, was so great that sight through them was no longer possible, and that some lesser sagging of the other pipes had occurred. This was presumably due to insufficient compaction of some underlying backfill material, a circumstance which arose from unavoidable construction site activities. Any sag of a rod will result in an increase of the measured gap at its end. If a rod of length L sags into a circular arc, with its mid-point deflected a distance σ downwards from its position when straight, then the gap will lengthen by an amount δg given approximately by

$$\delta g \cong 8\sigma^2/(3L) \qquad (3)$$

The numerical factor depends on the shape of the sag, but to a first and sufficient approximation, the dimensional factor must be σ^2/L for any shape. The inverse dependence on rod length and direct dependence on the square of the sag distance should be noted. Some gap measurements made in only one manhole over the first few days after installation and not included in the strain analysis, were quite consistent with the extent of sag observed at that time. These initial measurements also showed a rapid decrease in the rate of change of gap lengths, and without further disturbance it may be supposed that at present any remaining settlement should be negligible. Unfortunately, continued construction operations at the Te Marua site and variations of ground water level may continue to cause vertical flexure of the rods, and it is not certain that this would always be downward. There is also no reason to suppose that all rods will suffer the same flexure, though the sense may be the same. If gap measurements are used to estimate rod flexure alone, as they can be, then it is not possible to estimate any horizontal strain components nor fault creep, and the purpose of the experiment would be frustrated.

The only reasonable assumption is that the two diagonally-crossing rods suffer similar flexures since they cross near their mid-points and the pipes which carry them almost certainly remain in contact at their crossing as installed. The crucial point is that the gaps associated with these diagonal rods are most sensitive to the expected shear deformation, yet, since they have different lengths, their gaps will change differently from a given amount of mid point deflection, and their orientations are favourably disposed for this difference to be mistaken for a consequence of transcurrent creep on the fault.

In detail, if the two diagonal rods were each at 45° to the fault trace, then the estimated engineering shear strain, γ, right laterally parallel to the trace, would be the difference of the ratios of gap change to rod length.

$$\gamma = (\delta g/L)_{SM\text{-}NA} - (\delta g/L)_{NM\text{-}SA}$$

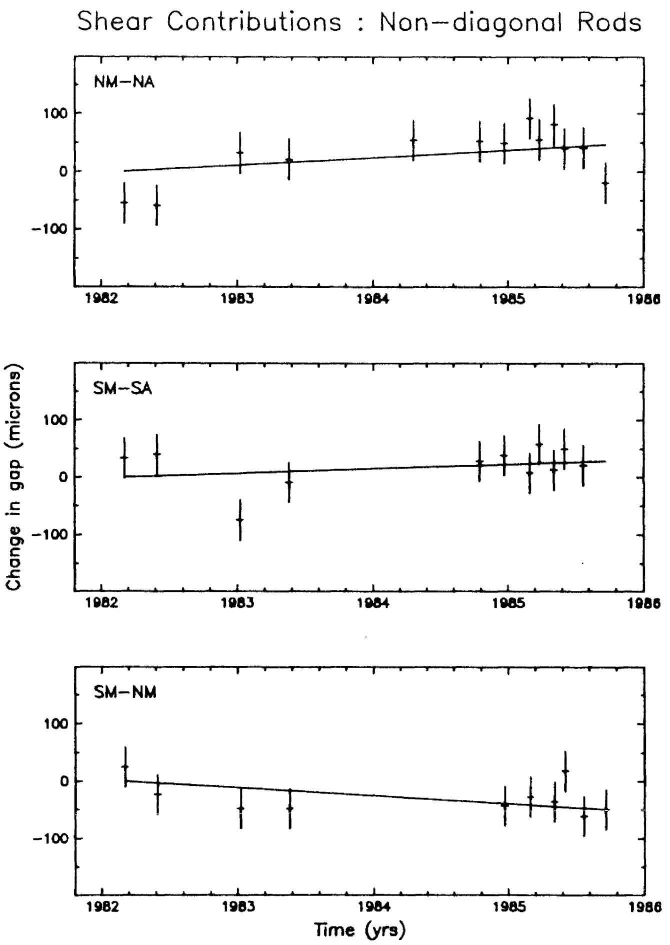
$$\cong 0.017\sigma^2 \times 10^{-6} \; (\sigma \text{ in mm}) \qquad (4)$$

This spurious shear increases rapidly with sag σ, and the total estimated shear, as derived in the preceding section, would result from about 30 mm sag of initially straight rods, or any 7 mm additional sag of rods already sagging 65 mm.

Moreover, any reduction in the sag, due for example to ground surface unloading or ground water changes, would appear as left-lateral shear or so-called "fault reversal" if incorrectly interpreted. Even if rod flexure does not cause the overall trends in Figure 4, it may cause the detailed variations.

The pipes were again inspected for visible sag in September 1985. Two more, NM-SA and SM-SA, are now sagging sufficiently that sight through them is no longer possible, leaving only one, NM-SM, with a sag less than its diameter of 65 mm. The array has therefore become highly sensitive to rod flexure.

It is not known when and how rapidly this sag occurred; any of the three dilatational maxima shown in Figure 3 may correspond to some sagging episode of sufficient magnitude. Only the first, however, has effects on the diagonally crossing rods consistent with their sagging equally, some 20 mm. The second and third maxima are quite unlikely to be entirely due to sag since the longer of the two diagonal rods, NM-SA, is affected to a much greater extent than the shorter,


Shear Contributions : Non–diagonal Rods

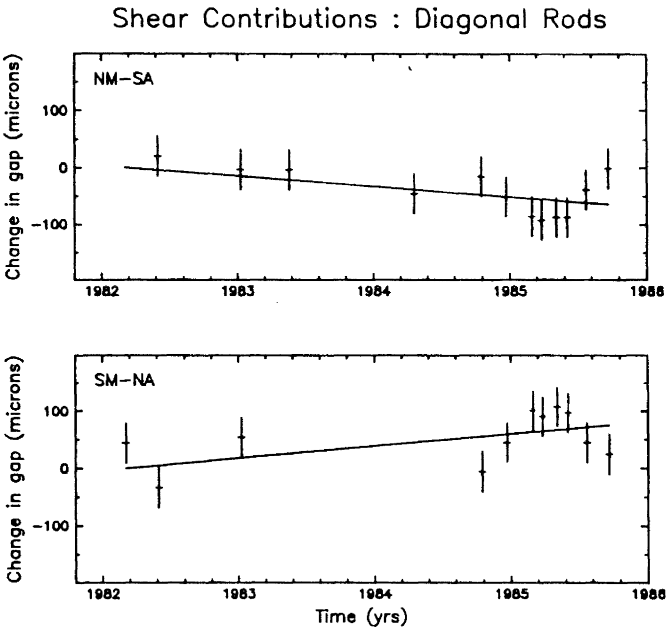

Shear Contributions : Diagonal Rods

FIGURE 4 : THE CONTRIBUTIONS TO MEASURED GAPS MODELLED AS BEING DUE TO SHEAR (POINTS WITH ERROR BARS), AND THE MODEL EXPECTATION (LINES). THESE ARE NOT REGRESSION LINES OF THE PLOTTED POINTS (SEE TEXT).

SM-NA, (the former lies under the latter at their crossing).

Despite these considerations, there is no secular upward trend in the plots of gauge measurements in Figure 2, indicating that the initial sagging has ceased. Episodic sagging and recovery may still occur from time to time. The strong dependence of gap length on flexure does, however, mean that some part of the estimated shear would then be spurious. It is of the utmost importance that some means of measuring the sag with, for example, suitably adapted inclinometers, be implemented if at all possible. It would be of great advantage to prevent sagging in any future similar installation.

CONCLUSIONS

A shear model which ignores rod flexure indicates the mechanical strain gauge measurements are consistent with right lateral shear deformation on the Wellington fault at an average rate of $(5 \pm 2) \times 10^{-6}$/yr (engineering units) since 1982. This would correspond to (25 ± 10) μm/yr displacement across the array. Consideration of the effects of rod sag shows some significant part of the estimated deformation may be spurious. It must therefore be considered as an upper limit to either fault creep or distributed deformation. This limit is two orders of magnitude less than the geologically determined average slip rate. If shear deformation is occurring, and is distributed broadly about the fault trace, it should be measurable by precise surveying methods. NZGS does already have a network of surveying monuments installed about the fault trace at Totara Park, a distance of some 5 km from the Te Marua site. This type of independent verification is necessary, even in the absence of the sagging problem, since the strainmeter experiment depends upon the stability of the four monuments. Some improvement in site stability is to be expected after construction activities cease.

ACKNOWLEDGEMENT

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