THE RESPONSE OF A FLEXIBLE PAVEMENT TO MOVING DYNAMIC LOADS

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1. ABSTRACT

A method for calculating the transient response of road surfaces is presented. The key assumptions are investigated and the theory is validated by experiments on an instrumented test track.

2. INTRODUCTION

When a heavy vehicle travels over an irregular road surface its tyre forces fluctuate. These "dynamic tyre forces" may cause large dynamic stresses and strains in the road structure. In order to examine the relationships between dynamic tyre forces and pavement deterioration, it is necessary to determine the transient responses (stresses,strains,displacements etc.) of roads as they are traversed by fluctuating tyre forces.

A variety of models have been used for analysis of the dynamic response of roads. A brief review of the literature can be found in [1]. The models fall into two main categories:

(i) A beam or plate supported by a uniform elastic (Winkler) foundation;

(ii) A structure comprising one or more layers of elastic or visco–elastic material.

The models vary in complexity according to the nature of the layers (elastic, damped elastic, visco–elastic) and the surface loading (moving, constant, harmonic). They are based almost exclusively on linear theory and few have been validated by comparison with field measurements. None of the models facilitate the transient (time domain) analysis that is required for road damage calculations.

3. THEORY

It is reasonable to assume that the response of the road structure and the dynamics of the vehicle are uncoupled. This is acceptable because the displacements of the road surface are small relative to the displacements of the vehicle, and the speed of propagation of elastic waves in road surfaces is typically 100m/s—600m/s [2] which is significantly greater than the speed of the vehicle.

The response of a single input linear system, $y(t)$, to a time varying input, $P(t)$, is given by the convolution integral:

$$y(t) = \int_{-\infty}^{\infty} h(t-\tau)P(\tau)\,d\tau, \qquad (1)$$

where $h(t)$ is the unit impulse response function relating the output to the input.

It is shown in [1] that for an n–wheeled vehicle, moving at speed V, Eq. 1 may be approximated by the following summation:

$$y(\rho,t) = \Delta\theta \sum_{i=1}^{n} \sum_{j=0}^{N_0} h(\mathbf{r}_i + Vj\Delta\theta\mathbf{i}, j\Delta\theta)P_i(t-j\Delta\theta), \qquad (2)$$

where ρ is the position vector of the response measuring point from a stationary origin, $\mathbf{r}_i(t)$ is the position of the measuring point relative to tyre force P_i, θ is the dummy variable of integration and $|h|$ is negligible for $\theta \geq N_0\Delta\theta$.

Thus the transient response of a pavement can be determined if its impulse response field, $h(x,t)$, can be predicted or measured and the applied loads $P_i(t)$ are known.

4. IMPULSE RESPONSE MEASUREMENTS

A programme of experiments was conducted on an instrumented test track at the Transport and Road Research Laboratory (TRRL), during the summer of 1987. It was directed towards testing the assumptions of the theory described above and validating the results.

The test section was constructed of approximately 200 mm of asphalt on 300mm of crushed granite subbase. This is a weak pavement by UK motorway standards. It contained buried transducers at two locations,3m apart. At each location there was an LVDT-type strain gauge mounted vertically at a depth of 650mm below the surface and a resistance foil strain gauge bound to the underside of the roadbase, transverse to the direction of the road. Both sets of gauges were in the nearside wheelpath. The output of the vertical LVDTs will be referred to as the "soil strain" and the output of the foil gauges as the "base strain".

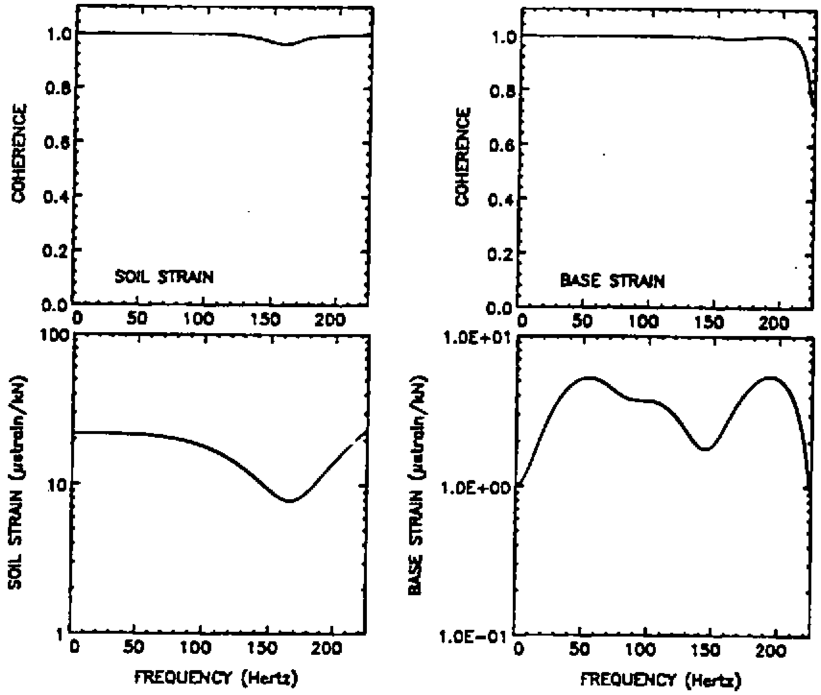

Fig.1. Magnitude of transfer functions and coherence functions relating the hammer force to measured strains

Impulse responses were measured using an instrumented hammer. The head of the hammer had a mass of 18.6kg and a diameter of 125mm and was mounted on a light, 2m long arm. The acceleration of the head was measured with an accelerometer and thus the force applied to the road during the impulse was calculated. The hammer was designed so that the peak force would be approximately 40kN — a typical tyre load.

The outputs from the buried strain gauges were measured using AC bridge circuits and all the data was logged with a digital data-logger controlled by a microcomputer.

4.1 Repeatability Tests

The repeatability of the impact tests was established by dropping the hammer several times at the same position and comparing the road responses. The comparison is obtained most effectively from the coherence between the input and output. The magnitude of the transfer function and the coherence function are shown in figure 1 for impacts directly over the gauges. It is clear that the equipment gives very repeatable results since the coherence is close to 1.0. As the distance between the hammer blow and the gauges is increased the response falls off, the signal to noise ratio decreases and the coherence falls accordingly. At a distance of 3m from the gauges the hammer excites negligible response.

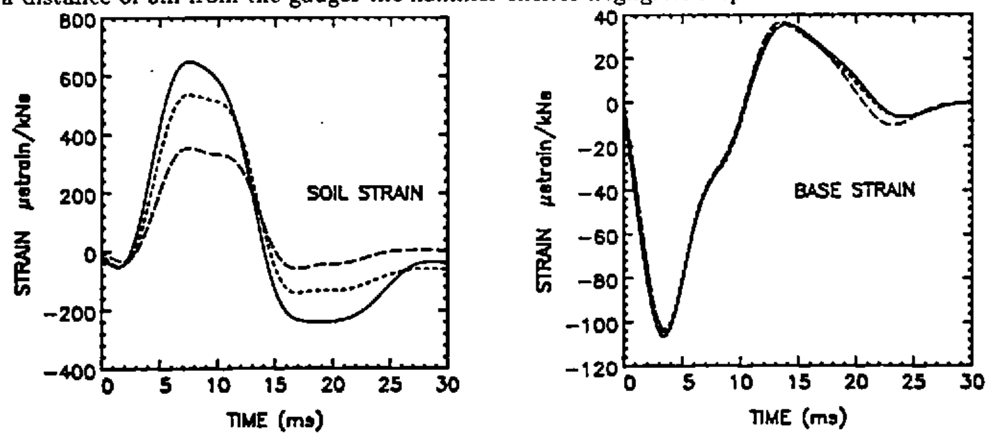

Fig.2. Normalised impulse responses due to different sized impulses
Hammer height: ----0.5m, ······1m, ——2m.

4.2 Linearity Tests

It is an assumption of the theory that the road behaves as a dynamically linear system. The literature is inconclusive on this point [3,4]. To investigate the linearity of the road the hammer was dropped at a distance of 1m from the gauges from different heights. The head was released 10 times from 2m, 1m and 0.5m above the surface. The applied impulse is proportional to the square-root of the height from which the hammer is dropped. The normalised impulse responses are shown in figure 2.

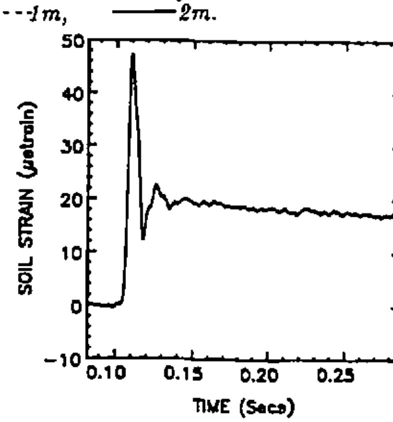

Fig.3. A soil strain response showing sticking in the gauge

The base strain response is essentially linear because the normalised responses are not affected by the magnitude of the applied impulse. The soil strain response, however, indicates a nonlinearity in the system causing a response similar to a softening spring. One nonlinear constituent in a system makes the whole system nonlinear, so it would appear that either the base strain is independent of the properties of the soil, or that the nonlinearity is introduced in the soil strain measuring system.

The situation is clarified if we examine records taken when the hammer was 2m from the gauges and the soil strains were much smaller. It was found that the LVDT-type strain gauge sometimes remained offset after the impulse response (see figure 3). This indicates some friction in the gauge, or inelasticity in the disturbed soil immediately surrounding the gauge, which would account for the nonlinear response.

It is concluded that under these operating conditions the road behaved essentially linearly but that some nonlinearities may have been introduced by the measuring system. The effect of any nonlinearities in the system are minimised by using a hammer which supplies a force of magnitude similar to typical wheel loads [5].

4.3 Isotropy Tests

The convolution calculation relies on the assumption that the impulse response is not a function of the absolute position along the wheelpath but only of the separation between the input and output. To investigate this assumption the hammer was dropped five times at each of four positions around a set of gauges. Each position was 2m from the gauges; two were on the wheelpath and two were perpendicular to it.

The soil strain-gauge was mounted vertically so that the same response was expected from each loading position. Conversely the base strain-gauge measures a directional strain and a bigger response was expected for hammer blows off the wheelpath to those on it. The results are shown in figure 4.

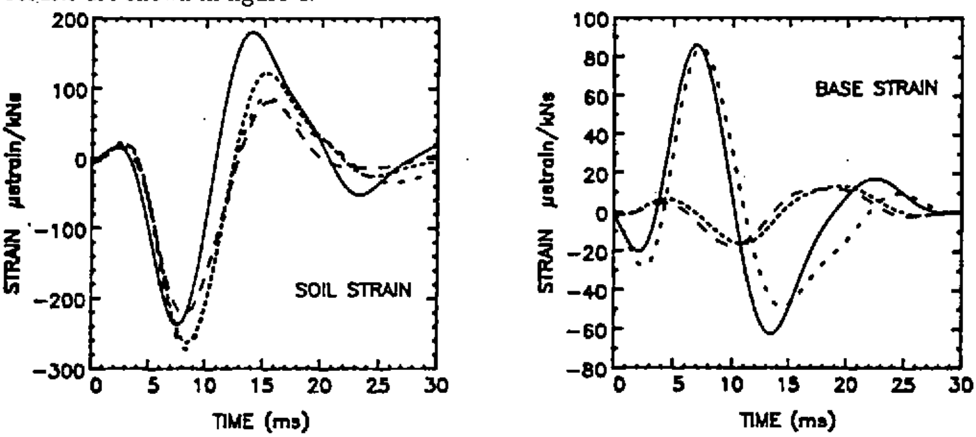

Fig.4. Impulse responses due to hammer blows at four points around the gauges

There are small differences in the responses indicating that the road may not be perfectly isotropic. The differences in the soil strain response may indicate that the soil strain-gauge was not perfectly vertical. Further investigation is required to confirm this.

4.4 Temperature Effects

Road responses vary significantly with environmental conditions and especially the temperature. To monitor this effect the surface temperature of the road was measured as each impulse was taken. Figure 5 shows the variation of peak normalised strain response with the surface temperature of the road, for an impulse applied directly above the gauges.

There is clearly a correlation between the surface temperature and the peak responses but

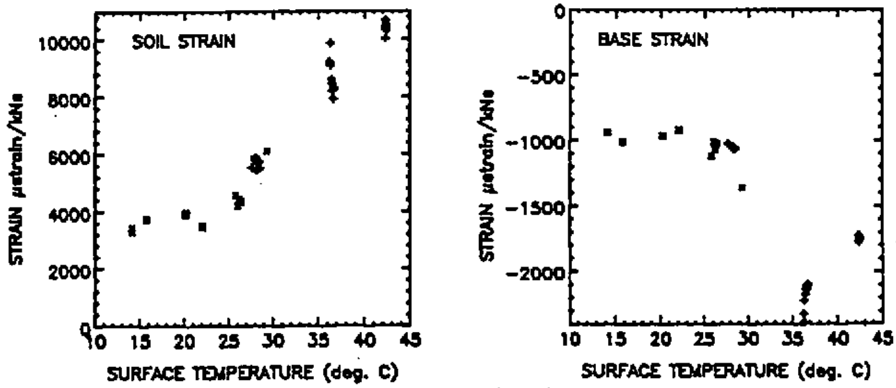

Fig.5. Peak impulse responses as a function of surface temperature

it should be noted that the surface temperature is not always indicative of the overall temperature distribution of the road structure. The daily variation of the temperature was measured during the testing period with four thermocouples imbedded in the road structure. As a result it was decided to measure the impulse response of the road immediately before the lorry runs, and very early in the day to minimise the effects of solar heating of the road.

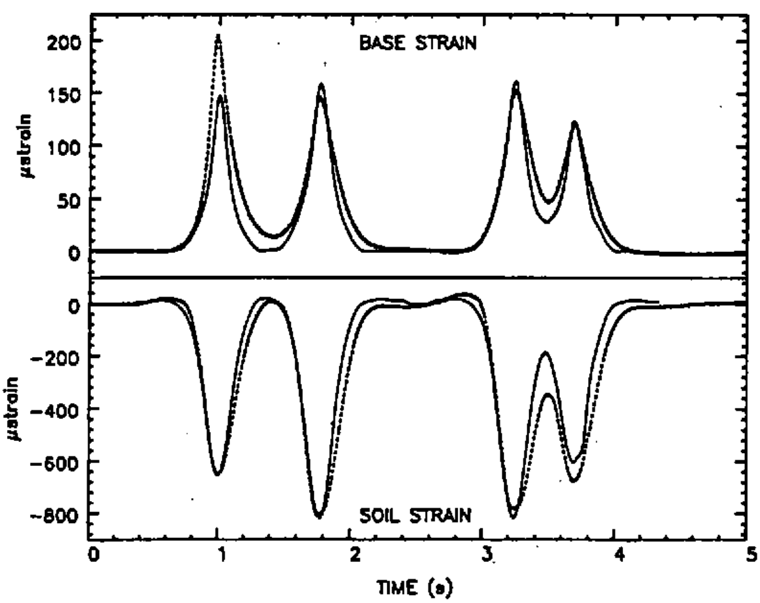

Fig.6. Base and Soil Strain responses: Vehicle speed 15km/h
Calculated Response ——— *Measured Response* ··········

5. RESPONSE TO MOVING VEHICLE LOADS

5.1 Description of Experiments

A four-axle articulated lorry was instrumented so that its tyre forces could be logged by an on-board analogue tape-recorder [6]. The vehicle was driven over the instrumented section of the test-track in the half-laden and fully-laden conditions at nominal speeds of 15.50 and 80 km/h. In each test the lorry was driven over the measuring points with the outside tyre of the three sets of dual-tyres (and the single tyre of the steering axle) passing directly over the gauges. The position of the vehicle was monitored by three infra-red beams which put pulses on the recording tape corresponding to known positions on the road. Simultaneously, pulses were recorded by the roadside data-logger which also logged the pavement strains.

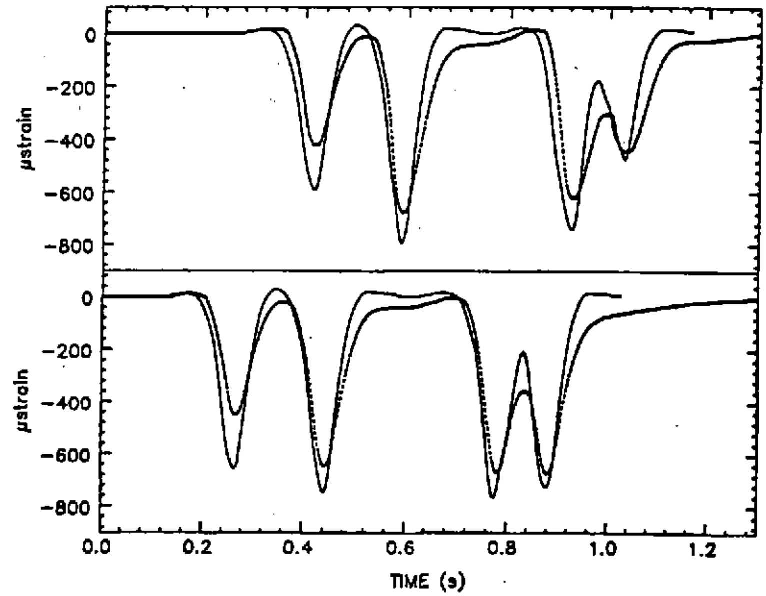

Fig.7. Soil Strain Responses at two positions along the wheelpath at 80km/h
Calculated Response —— *Measured Response* ········

5.2 Details of the Calculation

The numerical convolution calculation described in section 3 was used to combine the measured wheel forces with the measured field of road surface impulse responses. The calculation was performed for points spaced at 50mm intervals along the nearside wheel track. Each tyre contact patch was considered to be of constant area (200mm×125mm). The dual-tyres were represented by two tyre contact patches with centre spacings of 300mm. This is expected to yield accurate soil strain responses but only approximate lateral base strains, which are not isotropic. The effects of the offside tyre forces on the nearside road responses were considered negligible.

5.3 Results

Two sets of typical results are provided in figures 6 and 7, which show the measured and predicted responses of the road as functions of time. Each figure has four main peaks corresponding to passage of the four axles.

Figure 6 shows the base and soil strains at the first gauge position for a low speed (15km/h) test. Agreement between the measured and predicted responses is generally good, particularly for the soil strains. The small errors in the predicted base strain peaks are thought to be largely due to the vehicle passing slightly to one side of the buried gauge position (off-tracking). The base strain response is significantly more sensitive to tyre location than the soil strains. This effect is worst for the first peak because the single steering axle tyre has a much narrower field of influence than the three following sets of dual wheels.

Figure 7 shows the soil strain response at each of the gauge positions for an 80km/h test. The tyre forces generated by the tandem trailer suspension changed considerably during passage between the two gauge positions. This resulted in a significant change in the relative heights of the last two strain peaks.

Errors in the predictions are thought to be caused by:

(i) Lateral off-tracking of the tyres from the strain gauge positions,
(ii) Inaccuracy in the exact location of the strain gauges,
(iii) Road surface temperature variations during the period between the measurement of the impulse responses and the lorry tests,
(iv) The influence of the forces generated by the offside tyres,
(v) Nonlinearity of soil strain gauge response, and
(vi) Dynamic contact area variations.

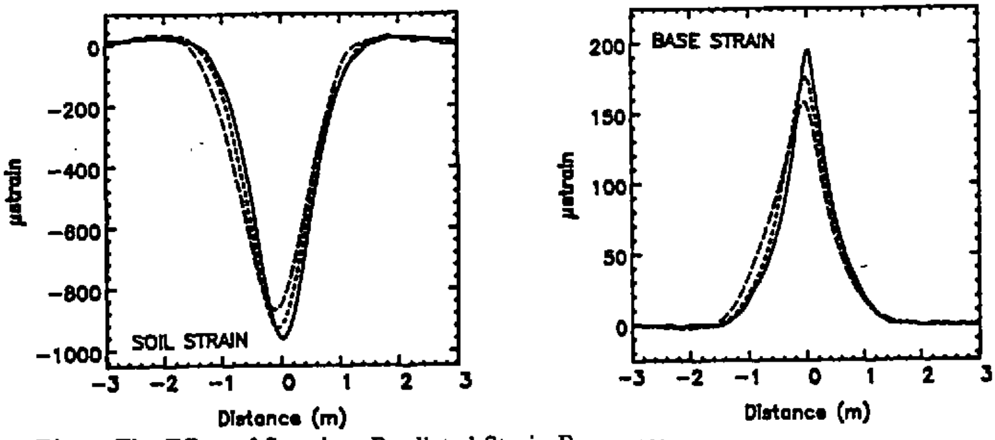

Fig.8. The Effect of Speed on Predicted Strain Responses
Speed: ——— *0m/s,* ------ *20m/s,* - - - - *40m/s.*

5.4 The Effect of Vehicle Speed

A number of authors have reported that the deflections of road surfaces are observed to decrease at high vehicle speeds [7,8]. This phenomenon is difficult to measure because of the increased variation in dynamic wheel loads at high speeds [6]. The convolution calculation provides an ideal tool for investigating this "speed effect".

The soil strain and base strain responses of the test track were calculated for a theoretical, constant 50kN load, moving at speeds of 0, 20, and 40m/s (0,72,144 km/h). Figure 8 shows the strain profiles in a frame of reference moving with the load.

The theoretical response of the test track decreases with speed. The soil strains decrease by approximately 10% and the base strains by approximately 20% between 0 and 40m/s. This is considerably less than previously reported by other authors [7,8].

6. CONCLUSIONS

(i) The assumptions associated with the numerical convolution method for calculating the dynamic response of road surfaces were investigated and the test road section was found to be linear and essentially isotropic.

(ii) The theoretical road response calculation was validated by comparison with full scale tests. Good agreement was found between experiment and theory. Some sources of error were discussed.

(iii) The theoretical response of the test road to a constant moving load was found to decrease by 10–20% for speeds between 0 and 40m/s.

7. REFERENCES

[1] Cebon, D. *Theoretical road damage due to dynamic tyre forces of heavy vehicles.* Proc. I.Mech.E., Vol.202 No.C2, 1988

[2] Jones, R., Thrower, E.N. & Gatfield, E.N. *Surface wave method.* 2nd. Int. Conf. on Structural Design of Asphalt Pavements, Ann Arbor, 1967

[3] Semenov, V.A. *Stress-strain state of a composite structure consisting of a stack of elastic plates on a multilayer granular base.* Soviet Applied Mechanics, March 1976 V12 N3 pp318–312

[4] Szendrei, M.E., Freeme, C.R. *Road responses to vibration tests.* Proc. ASCE., J. of the Soil Mechanics and Foudations Div. SM6, Nov. 1970 pp2099–2124

[5] Bendat, J.S., Piersol, A.G. *Random data analysis and measurement procedures.* Wiley, N.Y. 1986

[6] Cole, D.J. & Cebon, D. *Simulation and measurement of vehicle response to road roughness.* To be presented at ACOUSTICS '88, April 1988

[7] Anon. *The AASHO road test.* Special Report No.61-E Pavement Research, Highway Research Board, Washington, 1962

[8] Harr, M.E. *Influence of vehicle speed on pavement deflections* Proc. Highway Research Board, No.41, 1962 pp77–82

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