

MONITORING OF TRANSITION ZONES IN RAILWAYS

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ABSTRACT

Transitions between railway track on embankments or natural ground and fixed structures such as bridges and culverts often require substantial additional maintenance to preserve line, level and ride quality. This extra maintenance not only increases costs but also causes delays. Despite its importance for railway infrastructure owners, the fundamental cause of the poor performance of transition zones is not fully understood. To gain a better insight into the physical mechanisms involved, an extensive field investigation has commenced on a transition zone in The Netherlands. The transition zone consists of two reinforced concrete slabs which span between the normal track and a concrete culvert – a form of structure common on Dutch Railways. At the study location, the track is generally on a 4 m high embankment, initially built of sand, on top of a peat/clay layer 7 m thick. At a depth of 11 m below the track there is a natural sand layer, in which the piles that support the culvert are founded. The transition zone requires substantial additional maintenance. This paper presents data on the dynamic behaviour of the transition zone in response to scheduled passenger trains. Accelerations and velocities of the track, soil and approach slabs were measured, from which displacements were calculated. The dynamic track stiffness and the motion of the embankment and approach slab are also discussed.

INTRODUCTION

Transition zones between embankments and rigid structures such as bridges, tunnels and culverts are of major concern to the Dutch railway inframanager. This is due to the extra maintenance required (compared with normal track) to maintain line and level and hence passenger comfort. The extra maintenance is unpredictable, leading to higher costs and time delays, in opposition to the Dutch railway provider's ambitions to increase train speeds and reduce maintenance costs. As a first step towards addressing the problem by improving the understanding of transition zone behaviour, a Delft Cluster project was started in 2007 to study the performance of a typical transition zone. The project partners include Delft University of Technology, Deltares, ProRail (the Dutch railway inframanager) and the University of Southampton.

At present there are only limited experimental data on the behaviour of transition zones. Most experimental work has been performed on normal track, with attention focussed on wave propagation effects [Madshus and Kaynia (2000), Degrande and Schillemans (2001), SNCF (2005), ADIF (2005)]. Kolisoja and Mäkelä (2003) evaluated transition behaviour from a structural point of view, but obtained no significant information about the soil/track behaviour. Jenks (2006) and Lundqvist et al. (2006) presented track stiffness profiles, and determined relationships between stiffness and track degradation; both papers stated that the problems with transitions are due to the abrupt stiffness variation between the normal track and that on the structure.

To understand better the mechanisms that govern the behaviour of transition zones, a monitoring programme was undertaken on a typical transition zone on the Dutch Railways. This paper presents the results of part of that monitoring programme, focussing specifically on the dynamic behaviour of the transition zone. The results presented include measured dynamic velocities and accelerations of both the

track (sleepers and rails) and the soil. From these measurements, dynamic track deflections and the wave attenuation in the soil are evaluated. The effect of train loading is considered and discussed, together with the influence of the approach slab, which formed part of the transition zone design.

SITUATION

The transition zone chosen for the monitoring programme is located in the centre of the Netherlands, on a typical Dutch soft soil. The transition zone is between an embankment and a piled concrete culvert. The culvert is a 2 m by 2m square box constructed about 15 years ago to allow water flow between fields on either side of the embankment. The transition itself comprises 4 m long reinforced concrete slabs on either side of the culvert, hinged at the culvert end but with no special support provided at the embankment end (the 'free' end). The 'normal' track, away from the culvert and the transition, is supported on a 4 m high sand embankment built on top of a 7 m thick peat/clay layer. At 11 m depth (below track level) there is a stiffer sand layer, into which the piles supporting the culvert penetrate.

Figure 1 shows the results of two cone penetration tests carried out at the site. The discrepancies within and between the traces indicate that the embankment is quite heterogeneous. The very low cone resistance of the soft peat/clay layer confirms that its mechanical properties are poor, and there is a thin sand layer at about 8 m depth (Figure 1).

The ballast thickness was determined by means of trial pit excavations and ground penetrating radar. The initial ballast thickness (according to the design drawings) was 30 cm, but as shown in Figure 2, on top of the culvert the ballast is now about 80 cm thick. Above the free end of the transition slab the ballast thickness is about 1.2 m - much more than on the embankment. This is the result of years of maintenance, primarily comprising tamping and re-ballasting.

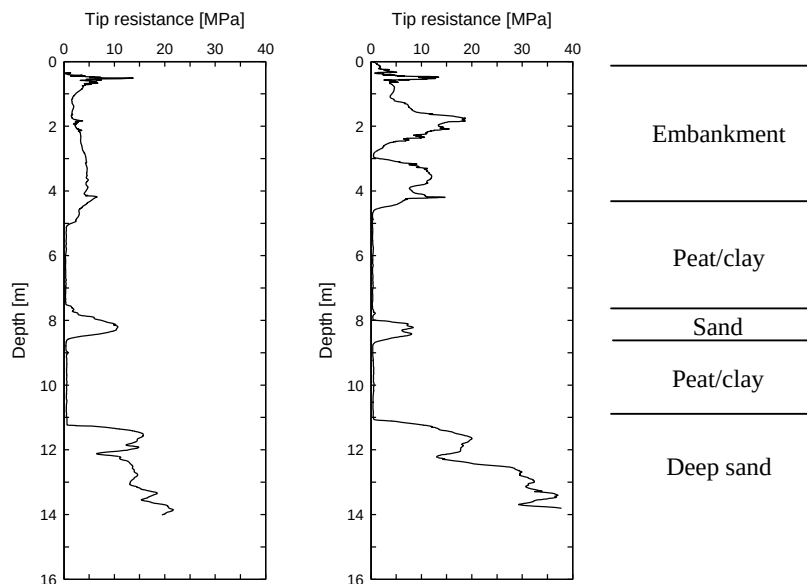


Figure 1 – CPT for two different locations

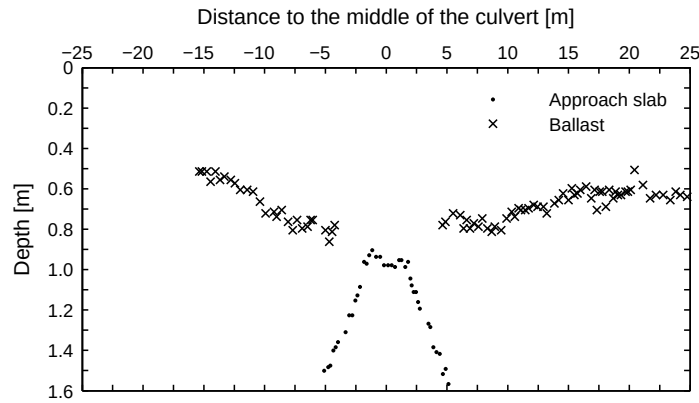


Figure 2 – Ballast thickness and approach slab position from Ground Penetration Radar

MONITORING PLAN

The dynamic measurements of displacement, velocity and acceleration were undertaken during scheduled train services. In total, 14 train passes were recorded with the types of trains shown in Table 1. 16 accelerometers (A), 11 geophones (G) and 1 video camera were used to measure accelerations, velocities and displacements of the track and soil, respectively. Figure 3 shows the locations of the geophones and accelerometers. Geophones were mounted both on the sleepers and within the soil; all of the accelerometers were located within the soil. Transducers G8 and A13 measured in the horizontal direction parallel with the track. Transducers A1-A2-A3, A4-A5-A6 and A7-A8-A9 were triaxial accelerometers, measuring in three mutually perpendicular directions (vertical, lateral and horizontal) at each of the three locations.

Table 1 – Train information

Train type	Number of train passages	Range of velocities [km/h]
Intercity double deck train set (IDD)	3	114-130
Intercity single deck train set (ISD)	4	98-129
Intercity locomotive + carriages (ILC)	2	126-130
Local train (LT)	5	89-114

RESULTS

Measurement validation

To provide a degree of confidence in the reliability of the data, one geophone (G9) and one accelerometer (A16) were placed at the same location (Figure 3). In addition, the displacements of the geophones located on the track were measured independently using a high speed video camera, following the approach of Bowness et al. (2007). This allowed cross referencing and validation of the measured velocities and displacements.

Figure 4 compares a typical displacement-time history obtained by integrating the geophone output with that recorded directly by the high speed camera for the same location. For the middle section of the train, there is close agreement between the two methods. At the front and rear of the train, the displacements calculated from the geophones appear somewhat greater than those recorded by the video camera. This

observation, and the offset in the geophone data is an artefact of the integration and filtering of the velocity data from the geophones

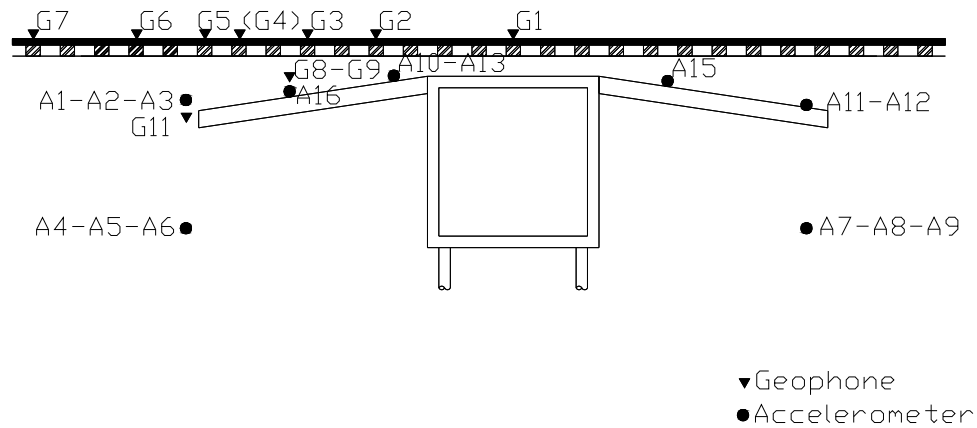


Figure 3 – Cross-section of culvert and transition slabs, showing instrument locations

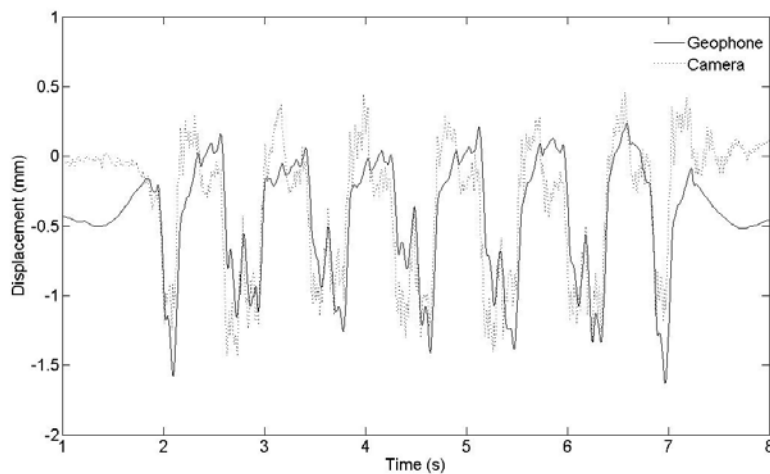


Figure 4 – Comparison of displacements obtained by integrating the Geophone data (G7) and those obtained from the video camera

Figure 5 compares the velocities obtained from accelerometer A16 with those measured by geophone G9. The velocities from the accelerometer were derived by numerical integration and filtering to eliminate low frequencies. Close agreement can be seen between the results from the two different devices in this case.

Track quality

Dynamic track displacements calculated from geophone velocities are presented in Figure 6 for three different sleepers (G1, G3 and G7 in Figure 3). The results show the response during one passage of an IDD train. Because of the way the geophone responds and the integration needed to obtain displacements from velocities, the mean displacement is shown as zero; however, comparison with the displacements recorded by the video camera shows that the actual displacement is in fact the peak to peak value (see Figure 4).

Figure 7 plots the maximum displacement at each location of the sleeper-mounted geophones, plotted against distance from the centre of the culvert. The largest displacement, and thus the lowest effective

track support stiffness, is associated with the approach slab. Similar results were obtained for all other train passages. The aim of the approach slab is to provide a gradual increase in stiffness, from the normal track on the embankment to the culvert. In reality, the stiffness reduces strongly at the free end of the approach slab before then increasing again near and over the culvert. Figure 7 shows that the maximum displacement on top of the culvert is half the maximum displacement of the normal track, but the displacement above the free end of the slab is about 8 times that above the culvert.

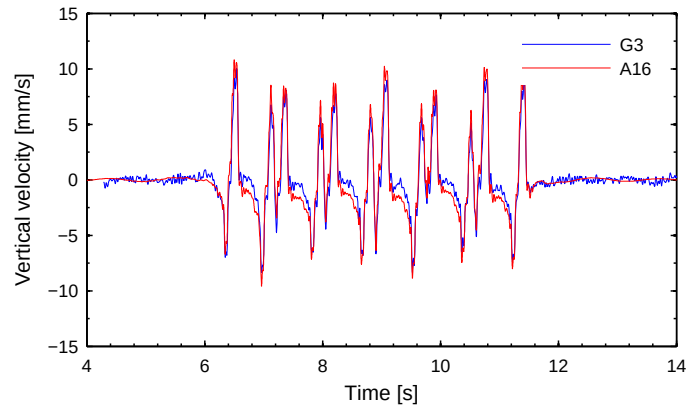


Figure 5 – Comparison between velocity data obtained directly from Geophone G9 and by integrating data from Accelerometer A16

The displacement records for the sleepers on top of the approach slab show a large upward spike just after the axles have passed. Numerical simulations by Varandas (2008) indicate that these peaks are likely to be caused by “hanging” (unsupported) sleepers combined with the increased stiffness above the culvert.

The results show that the intended behaviour of the approach slab, in gradually changing the support stiffness from that of the normal track to that of the stiff structure (culvert), is not being achieved. Jenks (2006) suggested that sudden increases in track support stiffness from a lower value in the normal track, to a higher value in the structure, gives rise to the excessive track degradation. The measurements show that, although the culvert stiffness is greater than the normal track stiffness, the stiffness of the transition zone is even less than the two zones of normal track on either side of it: this would be expected to increase, rather than reduce, rates of track degradation.

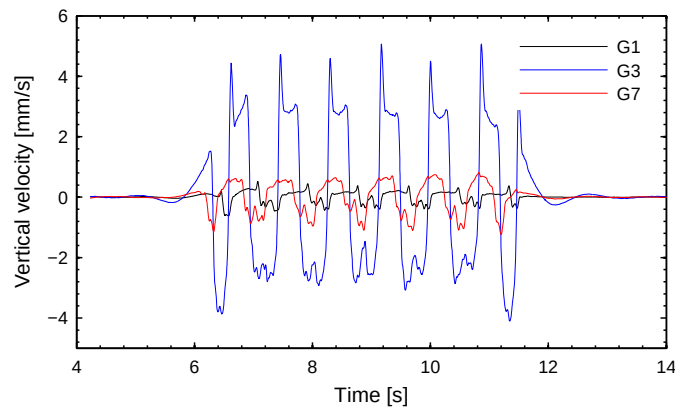


Figure 6 – Vertical track displacements obtained from Geophones G1, G3 and G7 during one passage of an IDD train

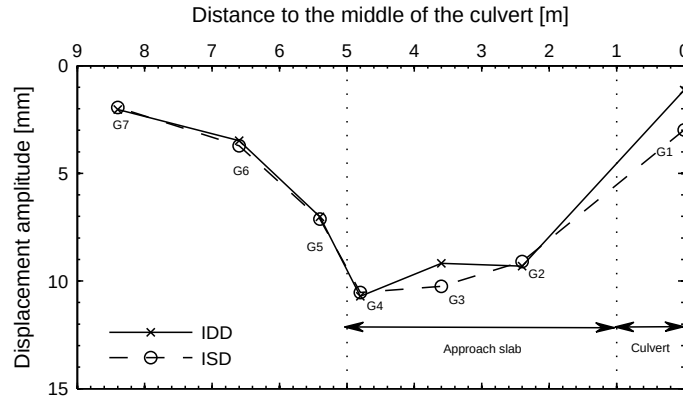


Figure 7 – Maximum vertical deflection of track against distance from the centre of the culvert measured by geophones during passage of an IDD and an ISD train

Figure 8 shows the frequency responses of the data in Figure 6. It can be seen that the dominant frequency for the dynamic displacement is about 1.5 Hz, which reflects the main frequency applied by the train loading (i.e. the frequency of passage of adjacent bogie pairs):

$$f_{\max} = \frac{\text{train velocity [m/s]}}{\text{wagon length [m]}} = \frac{36}{26} = 1.4 \text{ Hz} \quad (1)$$

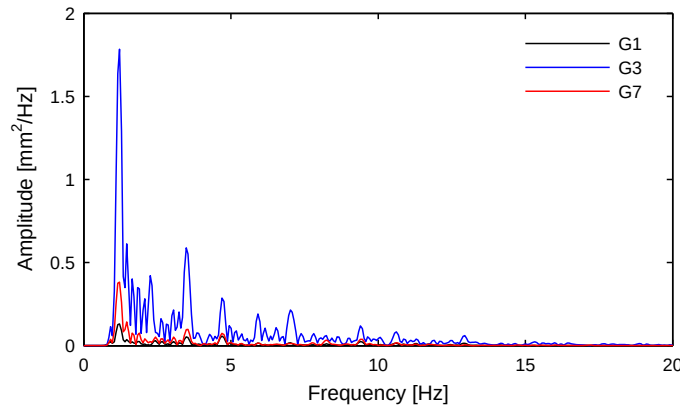


Figure 8 – Frequency response (FFT) for displacements a) centre of the culvert (G1); b) on top of the approach slab (G3); and c) the free track (G7)

Slab behaviour

One of the main objectives of the measurements programme was to evaluate the approach slab behaviour. In Figure 9 the vertical displacement for both the approach slab, as measured by geophone G9 (1m below sleeper level) and the nearest sleeper above G9, as measured by geophone G3, is presented. It can be seen that the displacement of the approach slab is about 1/8th that of the sleeper. This is interesting, as it indicates that a significant amount of the displacement recorded at the track is not due to the deflection of the approach slab. It is believed that this is due to lack of sleeper support – arising because the sleeper is hanging, but a reduced ground stiffness above the approach slab cannot be excluded.

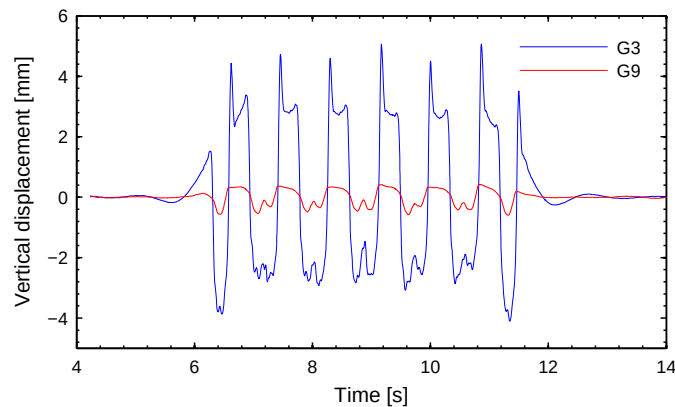


Figure 9 – Comparison between vertical displacements at the sleeper (G3) and on the transition slab (G9)

Ground behaviour

The vertical ground velocities in the embankment, just outside the transition zone, at depths of 1 m and 3 m below the top of the ballast were determined, by integrating the output from accelerometers A1 and A4, for a variety of train types and speeds (Figure 10). Velocities rather than displacements are presented because the latter require a second integration step which gives rise to significant low frequency errors that dominate the signal (Worden (1990)). In dynamics, the velocity is directly related to the stress.

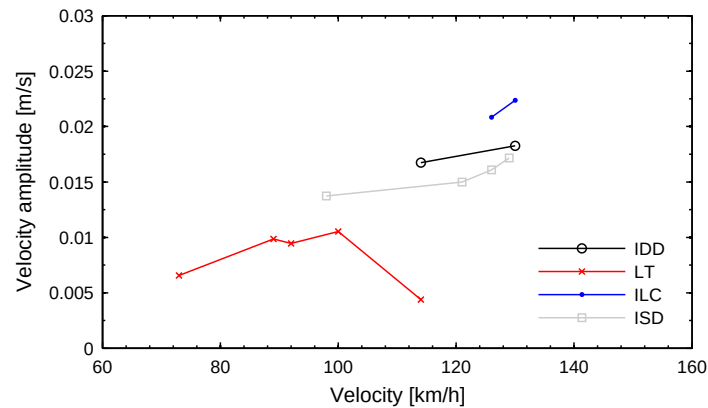
On the basis of the Boussinesq solution for a static point load applied to the surface of a homogeneous isotropic linear elastic half space, it would be expected that the vertical stress at a depth of 3 m would be $1/9^{\text{th}}$ of that at a depth of 1 m (the stress relation with depth being $1/z^2$ where z is depth). From Figure 10, it can be observed that the calculated velocities, and by association the displacements, at 1m depth are only around 50% greater than those at 3 m depth. This would indicate that the embankment layer between 1 m and 3 m depth beneath the track is moving like a rigid body on top of the soft layer.

Figure 10 shows an apparent peak in the velocity amplitude for the LT train between 90 and 100 km/h. This might be taken to suggest some type of resonance effect, where the loading frequency (a function of train speed and axle/bogie spacing) induced by the train approaches the natural frequency of the ground. However, no such peak is observed for any of the other train types monitored, for which the maximum velocity increases monotonically with train speed. Furthermore, Madshus and Kaynia (2000) showed that at or near resonance the ground displacements are out of phase with the axle loads, and that the ground displacement vs time profile is non-symmetrical. In this case, the displacement histories calculated from the geophones (e.g. Figures 6 and 9) are for all trains substantially symmetrical and in phase with the axle/bogie loads. This suggests that the apparent peak is not related to resonance effects. If the LT train with the highest speed is ignored, Figure 10 indicates a general trend of increasing vertical ground velocity with increasing train speed for all train sets. This is consistent with work by Yang *et al.* (in press) and Priest and Powrie (in press) who show that below the critical velocity the ground movements increase with train speed and hence velocities and accelerations. However, the resonance hypothesis cannot be completely disregarded based on this data. A new monitoring programme will be conducted in the near future, in which train loads, sleeper and ground velocities (and accelerations) will be measured, for a greater number of train passages. This will allow a better assessment of the behaviour of the transition zone and whether a resonance phenomena occurs.

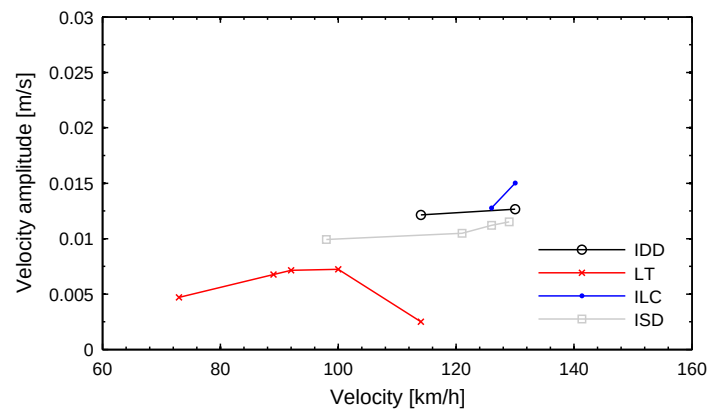
CONCLUSIONS

This paper has reported a field investigation into the dynamic behaviour of a transition zone during regular train services on a section of railway track in the Netherlands. Results presented included the current position and make-up of the track bed and the approach slab, as well as the soil dynamic response (accelerations, velocities and displacements) at different depths.

A comparison of results from different devices (accelerometers vs geophones for velocities, and video measurements vs geophones for displacements) allowed an assessment of the validity and consistency of the data to be made. This enabled the conclusions to be drawn with confidence and has provided useful



a)



b)

Figure 10 – Ground vertical velocity amplitude vs train speed measured by Accelerometers at depths of (a) 1 m (A1) and (b) 3 m (A4)

information for the development of more detailed instrumentation programme for future field monitoring at this and similar sites.

The results have demonstrated that the track has possible hanging sleepers above the approach slab. Instead of the desired increase in stiffness across the approach slab running from the normal track to the culvert, it was found that over the approach slab the stiffness was much less than either the normal track or the culvert. The reduction in track support stiffness was considerable, with observed vertical displacements being about 8 times greater on the approach slab than on the normal track.

Displacements in the ground at a depth of 1 m were only about 50% greater with those at 3m depth, which is unexpected considering the assumed reduction in stress (and hence displacements) with depth given a static analysis. This suggests that the embankment is moving as a rigid mass on a soft layer. A general trend of increasing ground deformation with increasing train speed, consistent with previous work, was identified.

ACKNOWLEDGEMENT

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