Track21: Report to International Scientific Panel Steering Group Meeting

Work Area 1: **Railway foundations / sub-base**

Initial Objectives

1.1 To investigate the response of soils of different type and degree of saturation to stress paths representative of train passage, with an emphasis on the effects of axle load and number of loading cycles.

1.2 To investigate the volumetric and shear strains that occur in clay soils – especially embankment fills – as a result of seasonal changes in pore water pressure arising from vegetation and climate effects, with a particular emphasis on the changes in these cycles that will result from climate change.

Key Activities

1. A number of soil specimens with different percent clay content have been tested in the hollow cylinder apparatus (HCA) with local strain instrumentation, to determine the effect of clay content on the response to cyclic loading with and without principle stress rotation.

2. A programme of field and laboratory tests has been carried out to investigate the influence of seasonal variations in pore pressure on clay slope behaviour. Field studies used a double ring infiltrometer to measure the vertical permeability of a clay slope at different times to assess seasonal changes in permeability. Laboratory triaxial testing of embankment clay fill material was carried out to assess the response to changes in pore pressure as experienced during seasonal wetting and drying cycles, and the possibility of fatigue failure in this stress path.

Key Outcomes

1. Results from HCA testing have confirmed that for some soils permanent strain accumulates at an increasing rate when more realistic loading conditions, representative of those experienced by a soil element during trafficking, are applied. Tests on four different soils (representative of typical engineered fills) have shown that increasing the clay content, at least up to about 16%, suppressed the build-up of pore pressure during undrained cyclic loading, leading to an enhanced resilience – although at some stage the reduced permeability will have a more significant adverse effect. This finding has implications for track design given the move to faster and heavier trains

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2. Irrecoverable strains may develop in clay embankment materials during cyclic changes in pore pressure representative of seasonal vegetation and climate effects. The accumulated permanent strain increases as the applied stresses approach the critical state. However, for stresses well below the critical state, the stiffness of the clay increases with the number of cycles. Field testing at a cutting in London Clay showed a cracked in situ vertical permeability in winter in the order of 10^{-8} m/s near the surface. This is two orders of magnitude greater than that of intact clay measured in triaxial tests (2.3×10^{-10} m/s). Field measurements taken during the end of summer 2012 (late September) showed the near surface permeability to be in the order of 10^{-6} m/s – a further two orders of magnitude increase compared with the end of winter. This indicates the seasonality of the near surface permeability, probably associated with the opening and closing of the cracks, which back-analysis of field data has shown to have a huge impact on pore pressures within the slope and hence stability.

Proposed Future Work

1. The work using the HCA will be extended to consider unsaturated soil behaviour, reflecting the likely effect of climate change on shallow soils associated with transportation infrastructure.

2. Further triaxial and hollow cylinder apparatus tests will be carried out on reconstituted and intact specimens of clay embankment materials to establish the influence of increased traffic loading.

3. Further field monitoring and numerical modelling will investigate the significance of near-surface processes, vegetation and permeability on the pore pressures induced in an embankment or cutting slope, and hence seasonal movements and stability.

Work Area 2: **Ballast and sleepers**

Initial Objectives

2.1 To develop a complete understanding of the role and requirements of ballast grading in terms of internal stability, strength, resilient modulus, drainage and fines capacity in the context of a modern railway.

2.2 To investigate "soft" techniques such as fabric wrapping of the ballast (ballast bags), gluing, resin injection, geogrids and random fibre reinforcement.

2.3 To investigate different sleeper types and sleeper/ballast interface modifications such as under-sleeper pads.

Key Activities

1. Employing a technique we developed as part of an earlier grant, we used resin to recover from the field a number of intact samples of ballast, corresponding to different stages of its lifecycle. At a second step we intend to use CT scanning to quantify the structure of ballast in the recovered samples, i.e. particle and interparticle contact orientation, coordination number, etc. and determine how the structure, and therefore the mechanical behaviour, of ballast changes with traffic loads.

2. We have carried out "full scale" rig tests of track sections, reproducing track geometry and loads as realistically as possible in lab conditions. Two rigs are available, one accommodating a single sleeper under vertical and possibly horizontal load (Southampton) and one with three sleepers and the ability to apply vertical loads in succession (Nottingham.) Rig tests explore the effect of ballast grading, sleeper type and ballast/sleeper interface on the mechanical response of the track. Initial tests with a standard Network Rail ballast gradation and a standard concrete sleeper under cyclic vertical load have been carried out at Southampton. Comparative tests are currently being carried out at Nottingham. Pressure sensitive paper, which takes different shades of red depending on the pressure applied to it, has been used under the sleeper to visualise ballast/sleeper contacts as well as the maximum stress passing through each contact.

3. We have carried out triaxial tests on coarse angular sand, as well as a scaled ballast developed as part of an earlier grant, to gain insights on the possible benefits of random

fibre reinforcement. Polypropylene fibres of various lengths were used. Unlike the existing literature, the resulting material was treated as a three-phase one where solid, void and fibre species were quantified separately.

4. Building on an in-house code and a library of particle shapes created as part of a previous project (Southampton) as well as in-house approaches to using PFC3D (Nottingham), we developed DEM models and modelling techniques to gain insights on the micro-mechanics of ballast in different settings. Models of triaxial tests, box tests and a sleeper on a ballast layer have been developed and used.

Key Outcomes

1. Preliminary CT scan results from one of the field samples of ballast show lower void ratio (0.57) and higher coordination number (9.3) than expected. Particle orientation is mostly subhorizontal, with 60% of particles at 30° or less, and 80% of particles at 45° or less.

2. Rig test results for 3M cycles show the development of settlements (max. of about 6mm) and progressive stiffening of the ballast. The resilient range of deflection under the sleeper ends appears to remain constant, while the corresponding range under the sleeper middle progressively narrows; this possibly points to the ballast under the sleeper middle stiffening faster than the ballast under the sleeper ends, progressively causing the sleeper to bend. Results from pressure sensitive paper show clear differences between the middle and the ends of the sleeper in terms of the stress transferred.

3. Triaxial tests on fibre reinforced coarse sand showed that even small amounts of fibre (few percent by volume of solids) can dramatically increase strength and suppress dilatancy. Preliminary results show that increasing fibre content affects the volumetric response of the sand, while increasing fibre length increases the mobilised strength and the strain required for full mobilisation. Appropriate scaling laws are currently been considered.

4. DEM analyses have been successfully calibrated to reproduce triaxial tests on scaled ballast. The way the membrane is modelled as well as the corresponding correction can have a significant effect on the results at low stresses. Preliminary results show that sleeper shape may have an effect on the mechanical behaviour of ballast under cyclic loading, however analyses of more than a few cycles are prohibitively expensive and so very difficult to validate.

Proposed Future Work

1. Most ballast samples are waiting to be scanned. Some base methodology for processing has been developed, however this needs to be further refined.

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2. Different ballast gradations, incorporating a finer fraction, will be tested and their performance compared to that of standard ballast. Different sleeper types as well as sleepers with undersleeper pads will also be tested. A calibration has been produced for the pressure sensitive paper, with the aim of quantifying contact stresses. This will be further refined. Algorithms for identifying the number of contact points are being explored. Finally, the use of laser levelling will be trialled, with a view of determining lateral strains and the extent of ballast spread during loading.

3. Triaxial tests on fibre reinforced scaled ballast have now commenced. Preliminary results seem to confirm the insights gained from coarse sands, although more tests with longer fibres have been planned and are being carried out.

4. Use DEM modelling to better understand the effect of the membrane in triaxial tests under low confinement. Develop DEM analyses of cyclic loading of ballast that can feasibly accommodate a few thousand cycles at least. Develop DEM analyses that can accommodate fibre reinforcement.

Work Area 3: **Noise and vibration**

Initial Objectives

3.1 To measure the dynamic stiffness of track structure layers including the ballast in new, glued, softly-reinforced and other conditions; also the effects of sleeper pads, ballast mats and rail pads

3.2 To assess the implications of different sleeper/ballast/sub-base combinations on noise and higher frequency vibration using appropriate numerical models

3.3 To study variation in track support stiffness as a mechanism for vibration generation, in comparison with the known mechanisms of dynamic excitation by moving loads

3.4 To assess the effects of the sleeper/ballast layer, other track designs and sub-base variations on low frequency vibration generation and propagation.

Key Activities

1. Ballast dynamic stiffness measurement: two approaches have been developed to measure the stiffness and damping of ballast in the frequency range 50-500 Hz. The first makes use of the full sleeper test rig developed in WA2. A test method has been developed using modal analysis of the sleeper situated in the ballast under preload to extract the stiffness and damping at specific frequencies. The second is a bespoke test rig that has been designed and constructed to measure the dynamic stiffness under a range of preloads.

2. Roughness and decay rates: to obtain a better understanding of the noise situation on the UK network, field tests of wheel and rail roughness and track decay rates have been carried out. A dedicated device for wheel roughness measurement has been designed and constructed. Its performance has been benchmarked against other systems within the EU Acoutrain project. It has also been used to measure a number of wheels on various UK trains. A rail roughness trolley (CAT) has been purchased and used at various sites on NR. Track decay rates have been measured on NR and on the ISVR test track at various temperatures to determine the effect of temperature on the rail pad stiffness.

Key Outcomes

1. Several sets of measurements of ballast dynamic stiffness achieved on sleeper rig. These showed the dynamic stiffness did not change appreciably with load cycles.

2. Bespoke test rig for measurement of ballast dynamic stiffness across a wide range of frequency and preload has been designed and constructed.

3. Wheel roughness measurement device has been developed and used.

Proposed Future Work:

1. Ballast stiffness: further measurements on the sleeper rig for different ballast gradations, reinforced or glued ballast, under-sleeper pads etc (as planned in WA2/WA5). The bespoke rig will be used and results compared with those obtained on the sleeper rig. It will then be used to measure the stiffness of other ballast configurations and track components such as USP, rail pads, ballast mats etc. The results will be used with existing and new models to determine the effects on both ground vibration and airborne noise.

2. Roughness and track decay rate will be measured at a range of UK sites. NR are providing site access. It is intended to include track with different rail pads on concrete, timber and steel sleepers. A TWINS model of track with steel sleepers will be established and validated.

3. A 1:5 scale model track is under construction that can be used to test the acoustic radiation from the rails and sleepers in a controlled manner. This will include scaled ballast. Acoustic impedance measurements of this ballast will be carried out, something that has proved difficult in the field (within Acoutrain). The acoustic impedance of alternative (scale) ballast formulations can also be considered. Boundary element modelling will be carried out of the acoustic radiation and the influence of the ballast and the implications for rolling noise will be determined.

4. A model for vehicle/track/ground interaction in the time domain will be developed. This will allow the dynamic loading due to a train on the ballast and subgrade to be determined which will feed into more detailed modelling in WA1 and 2. In addition it will allow the critical speed of the track to be assessed including effects of soil layering and non-linearity.

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Work Area 4: **Field integration (Critical zone improvements)**

Initial Objectives

4.1 To identify the extent and likely causes of problems at critical zones (points and transitions), by means of data review and additional field monitoring, and using data from WA's 1, 2 and 3.

4.2 To assess the potential effectiveness of the interventions and component improvements identified in WA2 in reducing maintenance at critical zones, by means of appropriate numerical modelling.

4.3 Potentially, to assess the effectiveness of improvement and remediation methods in practice by exploiting opportunities to carry out further field monitoring.

Key Activities

A number of preparatory activities have been conducted. These have included:

1. The development and deployment of in-service train mounted instrumentation for assessing track performance over time. This has been deployed on two areas of the network to assess spatial track condition.

2. A distributed track mounted monitoring system that covers a 20-sleep length of track has been developed. This will allow a detailed estimate of changes in track stiffness over a local area.

3. A number of key sites on the Brighton mainline have been identified which currently have poor critical zones and likely to be renewed in the next 3 years. Trackside measurement of these sites has commenced to quantify their current performance with regard to track behaviour.

Key Outcomes

1. Installation of a bogie and car mounted in-service inertial measurement condition monitoring system on two vehicles in the UK (MerseyRail and Southern);

2. The development of algorithms to identify and assess critical zone;

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3. The initial development of algorithms to align multiple data sets, which is a first step in the processing required for degradation monitoring;

4. Validation of the distributed track mounted monitoring system. This system uses linear laser sensors and geophones to estimate changes in track stiffness over a local area. To date this has been tested on a three-sleep rig in the laboratory, with good resolution and accuracy.

5. Eight sites have been identified on the Southern region (on the Brighton Main Line), over which the in-service instrumented train will run, that will be subject to renewal in the near future. A preliminary investigation has been conducted on a level crossing and station approach to determine pre-renewal behaviour; the data highlight the reduction in track stiffness within these transition zones.

Proposed Future Work:

1. The development of further algorithms for critical zone assessment and degradation monitoring.

2. Identification of specific test locations on the MerseyRail network along with BML route to validate the measurement and analyses approaches developed.

3. The development of an online event identification database that can be used to store, map, share and batch process events and data sets.

4. “Before” and “after” monitoring at selected Southern region problem sites.

Work Area 5: **Laboratory integration (System integration)**

Initial Objectives

5.1 to investigate, holistically, the effects of the interventions and innovations considered in WA2 on track system performance, ballast settlement and breakage, and the influence of sub-base conditions (WA1).

Key Activities

Both STF and RTF facilities have undergone tests within the frame of WA2. These tests allow assessing different types of instrumentation and measurement of track behaviour characteristics, with an emphasis on innovative methods. Some effort has been spent on the challenging task of obtaining reliable pressure measurements under the ballast using pressure cells. The results presently available show a correlation between the load and the pressure on the subgrade, but further optimisation of this method is required in future tests in the Nottingham RTF. Special films reacting to pressure installed on the bottom of the sleeper give an insight on the load transfer between the ballast particles and the sleeper. Laser scanning of the ballast surface has been investigated and promises to be the most rewarding tool regarding ballast displacement measurement during the tests. The method shows promise in providing a three-dimensional representation of the ballast displacement during loading.

Key Outcomes

Initial tests have been performed in the STF and RTF and show encouraging results. The use of laser scanning as an innovative surface characterisation tool, and pressure-sensitive paper underneath the sleeper, has been assessed and shows real promise for future tests.

Proposed Future Work

The results of the other work areas i.e. the effect of subgrade, sleeper type, under-sleeper pad, ballast interventions (grading, reinforcement), noise, critical zones, economic and performance models, will be compiled to plan a parametric study regarding the best possible components of a railway track. This parametric study will require tests combining these different possible components in order to find their optimal combination.

Work Area 6: **Modelling integration (Performance, environmental and economic modelling)**

Initial Objectives

6.1 To develop appropriate models, grounded in fundamental science, to link the effects of the sub-base, ballast and track system to vehicle dynamic loading and ride quality

6.2 To determine the comparative whole-life financial and energy (carbon) costs and benefits of the sub-base, ballast and track systems proposed.

Key Activities

The bulk of the research in this work area will be based on results from the other work areas. Therefore, work has so far focused on the following tasks:

1. Carrying out a comprehensive literature review of the use of Life Cycle Cost Analysis (LCCA) for modelling infrastructure project costs and of Life Cycle Analysis (LCA) for infrastructure carbon footprinting. This review has focused on the application of such techniques in the rail sector, but has also included a more general examination of the procedures involved.

2. Producing a meta-analysis report on the impacts on, and values of, noise and vibration, reliability, journey time and ride quality.

3. Identifying data requirements for whole life cost and maintenance timing optimisation models.

4. Liaison with Network Rail to obtain access to modelling datasets including ACTRAF, VTISM databases, GEOGIS, Network Measurement Train data and geospatial network data.

5. Identifying case studies for WA6 modelling work.

6. Developing a framework for modelling integration.

Key Outcomes

As stated above, the research in this area is still in its early stages, and therefore key outcomes so far comprise the literature review and meta-analysis listed in the previous section of this report. In conjunction with WA4, case study sites have been identified, including the Brighton Main Line and Merseyrail. At the Track21 Workshop on the 23rd and 24th August 2012 substantial progress was made in developing a Track 21 Engineering model framework that links mechanical models of track to stiffness and to track quality degradation.

Proposed Future Work

1. The first priority for this work area is to define the modelling case studies more precisely in discussion with researchers in the other work areas. It will then be possible to obtain the necessary data for these case study areas from Network Rail.

2. WA6 researchers will attend a Track-Ex training course in December 2012, following which a copy of Track-Ex will be supplied to the researchers by Network Rail.

3. Once these preliminary stages have been completed, work on developing the models in detail can commence, and at present it is anticipated that this milestone will be reached in early 2013. It is proposed that these models will comprise:

    a. A Track 21 Engineering model that includes mechanical models of sub-base, ballast and sleeper type; a model of stiffness that incorporates critical zones and vehicle dynamics and a model of track quality degradation.

    b. A modelling and appraisal procedure for the whole life financial, social and environmental costs of track systems and sub-bases. This will include use of LCCA, RAMS and hybrid-LCA procedures, implemented using both 'off-the-shelf' (such as VTISM and Changer) and bespoke modelling tools.

4. An optimisation tool for the timing and duration of track maintenance events. Again, this will make use of both 'off-the-shelf' (such as Track-Ex) and bespoke elements.

List of Outputs

Journal Articles (Published and In Review)

Dependence of shape on particle size for a crushed rock railway ballast (In review). L. Le Pen, W. Powrie, A. Zervos, S. Aingaran & S. Ahmed, submitted to *Granular Matter*, 2012.

Sleeper end resistance of ballasted railway track (In review). L. Le Pen, A. M. Bhandari & W. Powrie, submitted to *Geotechnique*, 2012.

The effect of enhanced curving forces on the behaviour of canted ballasted track (2012). J. Priest, W. Powrie, L. Le Pen, P. Mak, & M. Burstow, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, published online 14 September 2012, (doi: 10.1177/0954409712458623).

Condition monitoring opportunities using vehicle-based sensors (2011). C. Ward, P. Weston, E. Stewart, H. Li, R. Goodall, C. Roberts, T. Mei, G. Charles & R. Dixon, *Proceedings of the IMechE: Part F – Journal of Rail and Rapid Transit*, **225** (2), 202-218.

Contribution of base, crib and shoulder ballast to the lateral sliding resistance of railway track: a geotechnical perspective (2011). L. Le Pen, W. Powrie, *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, **225** (2), 113-128. (doi: 10.1177/0954409710397094).

Conference Proceedings

Innovative sleeper design analysis using DEM (2012). J.-F. Ferellec & G. R. McDowell, *Proceedings of the 2nd International Conference on Transportation Geotechnics*, Sapporo, Japan, 10-12 September 2012.

The lovely stones or never mind the ballast? The future for ballasted railway track (2012). W. Powrie, L. Le Pen, J. A. Priest, A. Zervos, T. C. Abadi, S. Aingaran & J. Harkness, Third International Workshop on Modern Trends in Geomechanics IW-MTG3, Nottingham, 4-5 September 2012.

Trackside measurement at railway critical zones using sensors and vehicle-borne instrumentation (2011). H. Kim, P. Weston, C. Roberts & J. Priest, *Proceedings of the 5th International Conference on Railway Condition Monitoring and NDT*, Derby, UK, 29-30 November 2011.

Strategies and Techniques to Support Railway e-Maintenance (2010). C. Roberts, *Proceedings of the 1st International Workshop and Congress on eMaintenance*, Luleå, Sweden, 22-24 June 2010.

Presentations

The effect of fibre reinforcement on the mechanical behaviour of granular materials (2012). Presented by O. Ajayi to ALERT Annual Workshop, Aussois, France, 1-6 October 2012.

TRACK21: Progress update (2012). Presented by W. Powrie to the Railway Infrastructure Association (RIA) Infrastructure Technical Group meeting on 19 July 2012.

On the right track? Sustainable materials in railway geotechnical engineering (2012). Presented by W. Powrie to the Low Impact Materials and innovative Engineering Solutions research Network (Limesnet), Research Workshop Bath, 15 May 2012.

Insights Into Railway Track and Earthworks Behaviour from Field Observations (2012). Presented by W. Powrie to the Permanent Way Institute (PWI), 10th floor, LU Headquarters, 55 Broadway, St. James' Park, London, 12 March 2012.

The development of structure in railway ballast (2011). Presented by L. Le Pen at the ITC35 UK Travelling Workshop GM3: GeoMechanics Micro to Macro, Imperial College, 18-19 December 2011.

Numerical modelling of triaxial tests on railway ballast (2011). Presented by J. Harkness at the ITC35 UK Travelling Workshop GM3: GeoMechanics Micro to Macro: Imperial College, 18-19 December 2011.

Magazine Articles

TRACK21: Railway track for the 21st century (Forthcoming). William Powrie presents an update on progress on the TRACK21 research programme, *Railway Strategies magazine*.

Reducing Noise and Vibration from Ballasted Track: Contribution of Track 21 Project (2012). D. Thompson, *European Railway Review*, Issue 6.

Track for the 21st Century (2012). W. Powrie, *Railway Technology Magazine*, 1 May 2012.

Track21: Railway track research for the 21st century (2011). W. Powrie, *European Railway Review*, Issue 2, 6 April 2011.

Rail's challenging climate (2011). A. Mourant, *Rail* 683, 16-29 November 2011, pp. 56-60.

Understanding the behaviour of embankments (2010). J. Smethurst, W. Powrie, *Railway Strategies*, pp. 73-75.