Recent Developments in LS-DYNA for Civil Engineering

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Introduction

- LS-DYNA has well-known applications for earthquake and blast/impact engineering
  - Building design development
  - Site response studies
  - Development of isolators and energy absorbers
- Arup have recently added new features:
  - Damping model for vibration studies
  - Material model - Rock and general Mohr-Coulomb
  - Staged construction
  - Pore water pressure analysis
- This paper will show some applications of the new features

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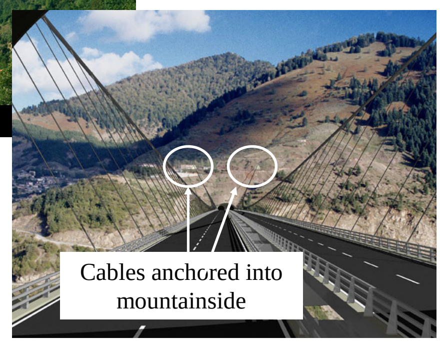

Metsovitikos Bridge, Greece - architect's impression of bridge superposed on photo of site

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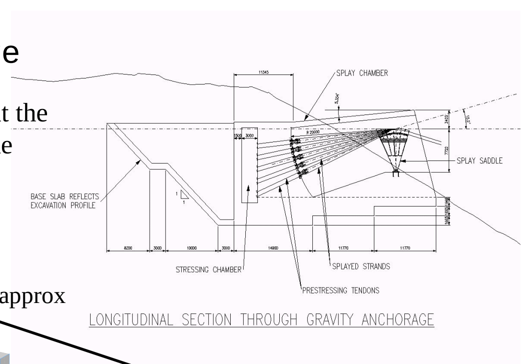
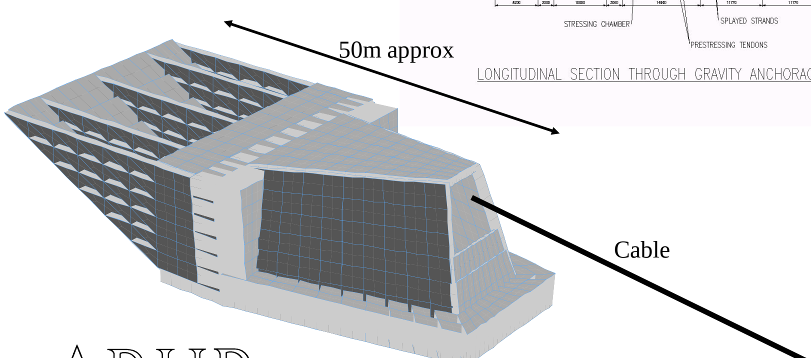
Concrete gravity anchorage

3D analysis was needed to prove that the anchor block would not slide, and the rock would not fail, when the cable tension was applied





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Analysis of rock anchor load capacity

- 3D analysis was needed to prove that the anchor block would not slide, and that the rock would not fail, when the cable tension was applied.
- The rock contains “joints” (planes of weakness) that must be included in the material model
- A well-established 3D implicit code was unable to solve the problem
- A specialist academic implicit code was tried, but run times were excessive for the 3D model
- LS-DYNA successfully solved the problem after a new material model was added

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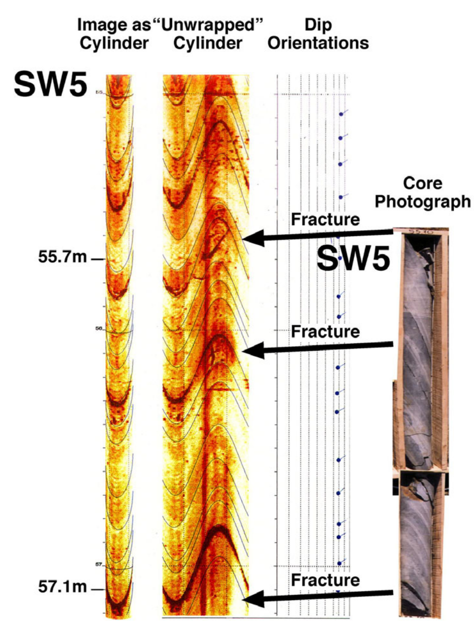
- Rock contains “joint planes”, uniformly distributed through the material. These can be characterised as having a friction angle but no tensile strength.



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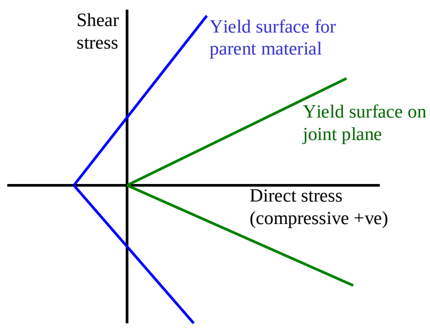
*MAT_JOINTED_ROCK - Mohr-Coulomb with joint planes



Yield surfaces for parent material and joint planes

- The user defines cohesion and friction angle for the parent material (the cohesion can vary with time, and all the properties can vary with depth)
- Up to 3 joint planes can be defined, oriented by “dip” and “strike” angles relative to the global coordinate system or local element axes. Cohesion is generally set to zero but the joints can be introduced gradually using a cohesion-vs-time curve.
- Utilisation (shear stress / maximum allowable shear stress) and slippage strains can be plotted, for the parent material and also for each joint.

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Applications of *MAT_JOINTED_ROCK

- There are several applications in civil engineering analysis:
  - Rock
  - General Mohr-Coulomb type material (set the number of joint planes to zero)
  - Masonry or blockwork can be simulated, by treating the mortar as joint planes

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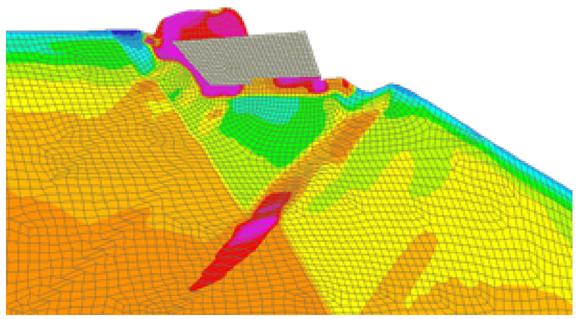
Verification of material model and results

- Comparison with hand calculation - 1 element tests
- Comparison with hand calculation for anchor block sliding - 2D model
- Comparison with other analysis codes - 2D model
- Checking by Mohr's Circle diagrams that no element exceeded the maximum shear criteria - 2D and 3D models

2D model used in verification



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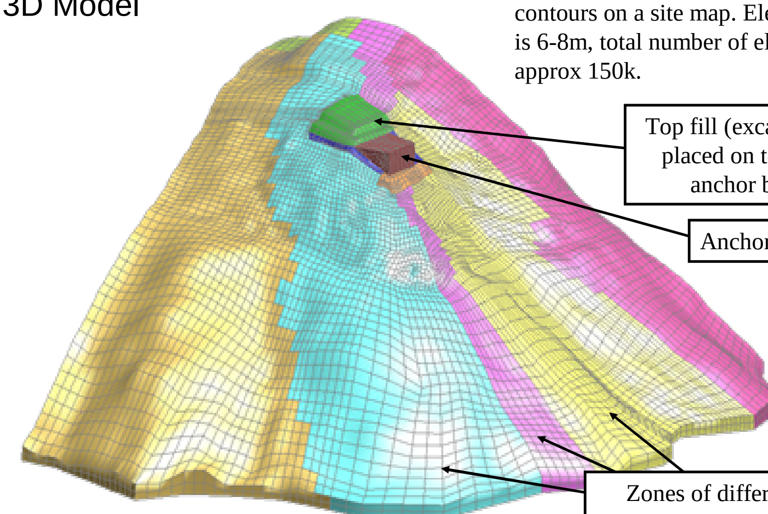
3D Model

The 3D model was meshed from contours on a site map. Element size is 6-8m, total number of elements approx 150k.



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Loading sequence

- The initial stress state of the rock must be modelled before loading the cable, because the strength of the material is stress-dependent. This occurs during thousands of years but we must model it much more quickly, but without inducing dynamic responses.
- Gradually apply gravity - initially the material has elastic behaviour
- Gradually reduce cohesion of material (parent material and joints) to the correct values - the mountain sinks slightly and parts of the surface slide
- Gradually apply weight of anchor block
- Gradually increase cable load until failure occurs

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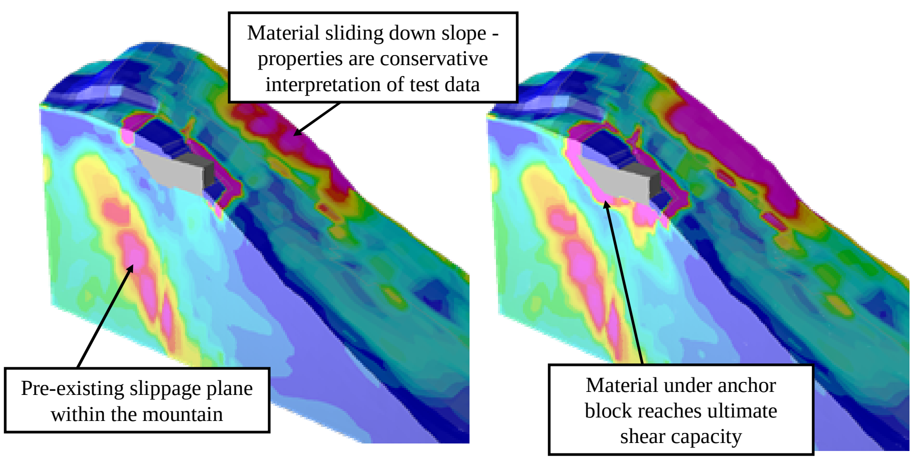
Typical result - shear strain on joint planes



Shear strain on weakest joint plane before cable load (left) and at onset of failure (right). Failure occurred only after the cable load exceeded twice the maximum design load.

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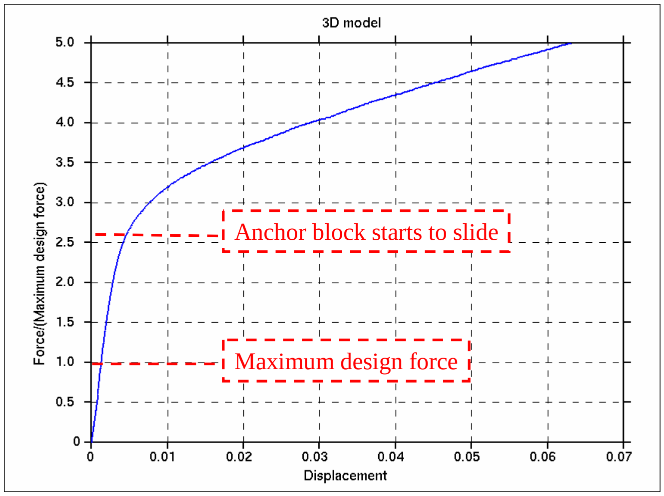
Force-deflection result



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Conclusions of rock anchor study

- Safety factor = 2 to 3
  - The maximum design load includes loads occurring due to wind, seismic action, etc
- Failure mode is sliding of the anchor block
- A well-established 3D implicit code was unable to solve the problem. Another implicit code was tried but took too long to run.
- LS-DYNA successfully solved the problem after a new material model was added. CPU time approx. 40 hours on engineering workstation.

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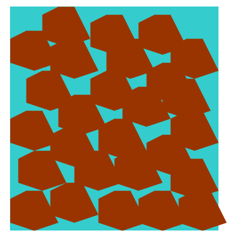
Analysis of soils

- Material models:
  - *MAT_DRUCKER_PRAGER
  - *MAT_JOINTED_ROCK (can be used as a Mohr Coulomb material)
  - *MAT_SOIL_BRICK (Special model for clay)
- Pore water pressure
  - Drained (e.g. sand - water pressure stays constant)
  - Undrained (e.g. clay - water is trapped in each element, and can become pressurised)
  - Time-dependent (seepage of water is modelled during the calculation - similar to heat flow calculation)
  - Several special keywords: *CONTROL_PORE_FLUID, *BOUNDARY_PORE_FLUID, *INITIAL_PWP_DEPTH, *LOAD_ADDED_PWP, *MAT_PERMEABILITY_option

Soil particles and pore water



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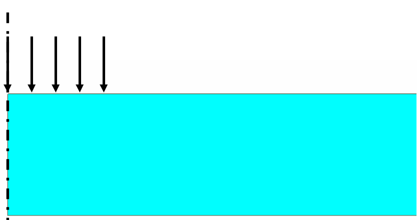
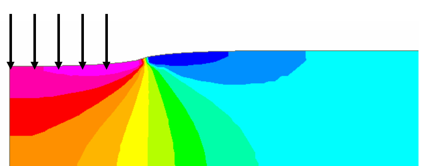
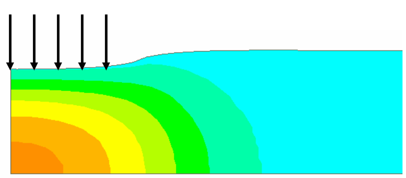
Example of time-dependent consolidation



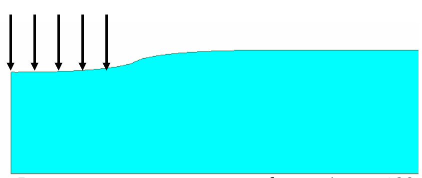
Load applied to symmetrical block of soil



Instantaneous build-up of pore water pressure, some initial settlement



Pressure reduces as the water seeps away



Pore pressure returns to initial state (time=100 days); extra settlement=12mm

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Staged construction

- In civil engineering, we often need to simulate the construction process
  - Excavation, temporary works such as props, pumping out of ground water, and adding new foundations and structure, subsequent consolidation of the soil
  - Buildings, dams, tunnels, etc
  - Check for collapse of new structure or retaining walls during construction
  - The sequence may be important in determining the final state of the soil and the amount of settlement

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New LS-DYNA keywords for staged construction

- All parts that will be active at some time during the construction sequence are present in the model initially.
- We run one single analysis, without restarts.
- Parts added or removed during construction are controlled with *STIFFEN_PART, *LOAD_GRAVITY_PART, *REMOVE_PART (functions of time)

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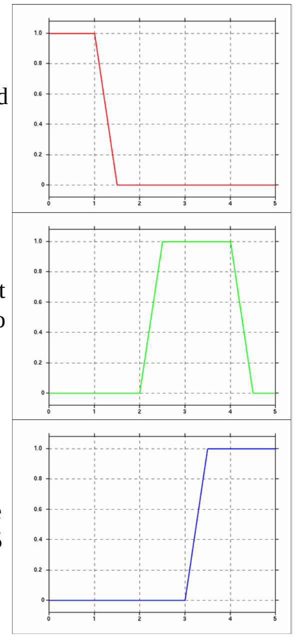
Typical curves

- Same curve for *STIFFEN_PART and *LOAD_GRAVITY_PART
- Factor = 1.0 - part is fully active and loaded by gravity
- Factor = 1.0E-6 - part has negligible weight and negligible stiffness - effectively inactive
- Curves should ramp gradually between 1.0 and 1.0E-6 to avoid dynamic effects



Soil excavated at t=1.5

Prop, present from t=2.5 to t=4

New structure added at t=3.5

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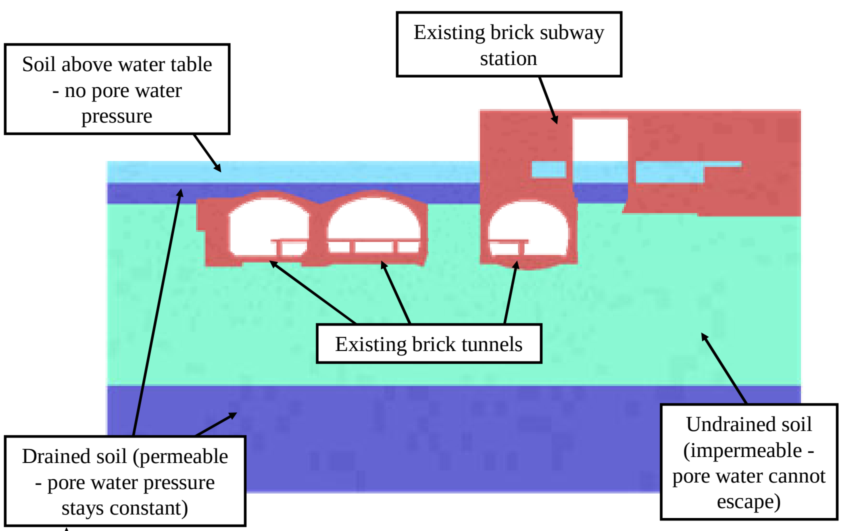
Typical application: redevelopment of a subway station



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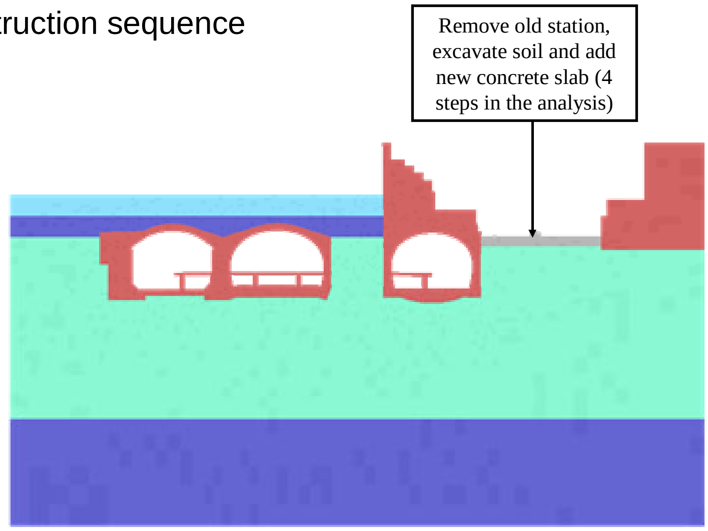
Construction sequence



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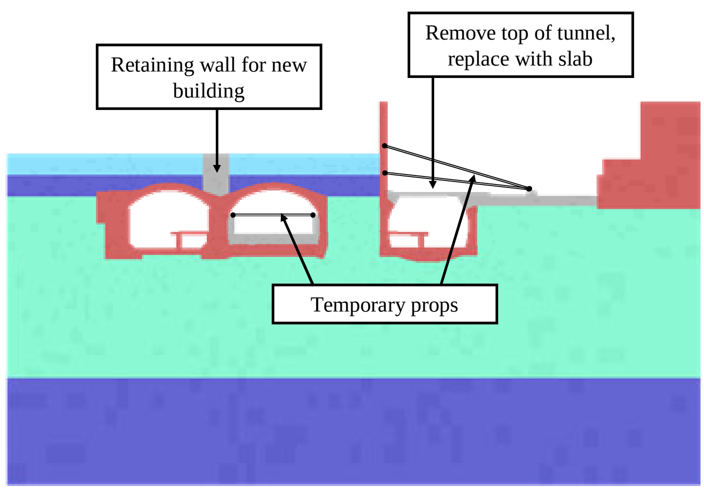
Construction sequence



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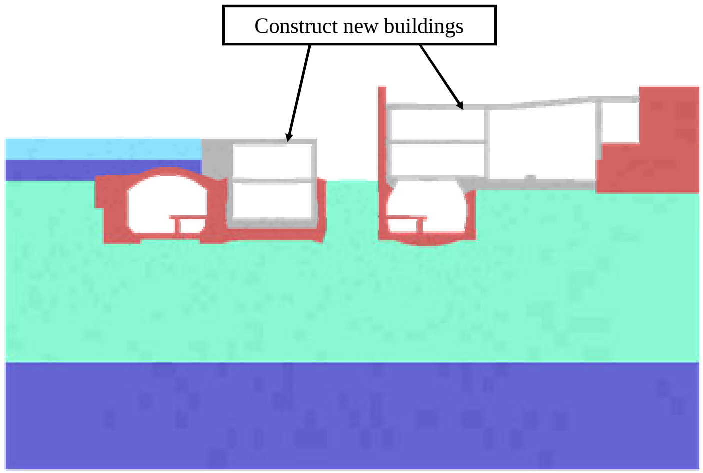
Construction sequence



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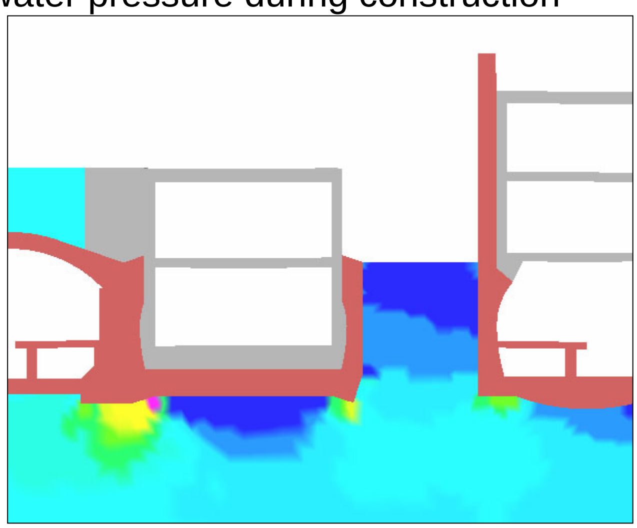
Excess pore water pressure during construction

Load on the structure arising from excess pressure in the water in the pores of the soil is included in the calculation. The pressure distribution is changed by the construction process.



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Notes on construction stages

- The LS-DYNA analysis has 11 stages, including application of gravity, removal of soil and old buildings, reducing pore water pressure (pumping), adding and removing temporary props (beam elements), and adding new construction
- The main purpose of the analysis is to check that the brick tunnels will not collapse at any point in the construction sequence - trains will continue to use the tunnels.

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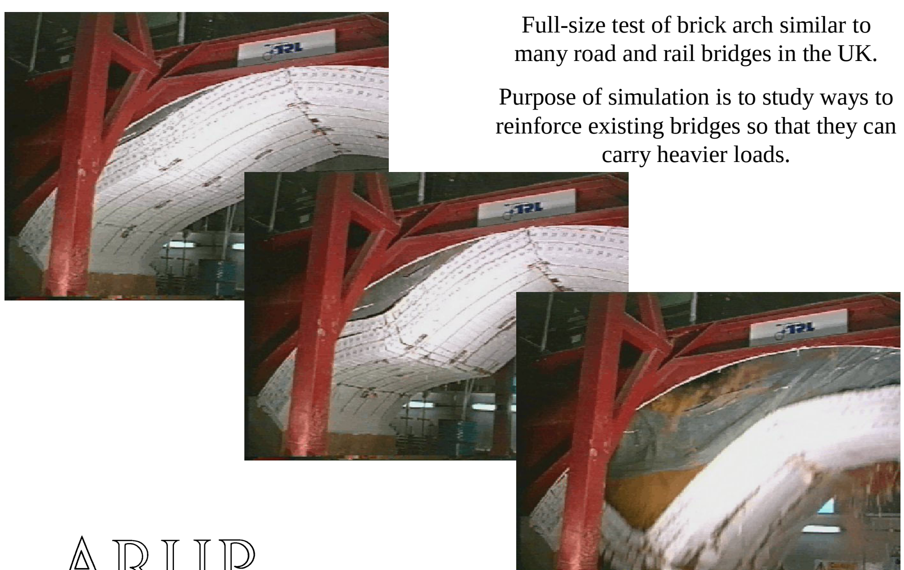
Eccentric load on brick arch - TRL test

Full-size test of brick arch similar to many road and rail bridges in the UK.

Purpose of simulation is to study ways to reinforce existing bridges so that they can carry heavier loads.



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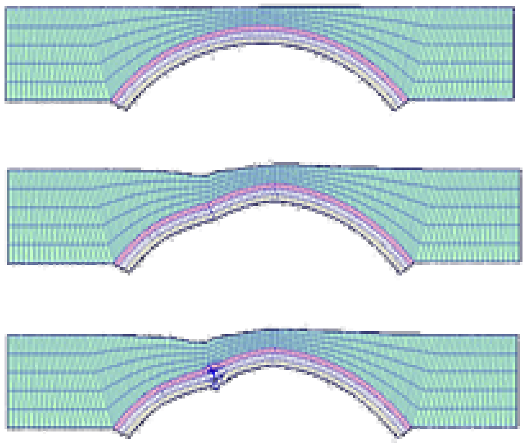
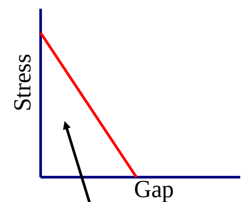
LS-DYNA model of brick arch



Each brick is modelled as a solid element, *MAT_ELASTIC

Mortar is modelled by *CONTACT_TIEBREAK_SURFACE_TO_SURFACE with a curve of stress vs gap opening



Area under curve = energy per unit area debonded (G_c)

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Predictive Structure-Borne Noise Analysis on Railway Viaducts

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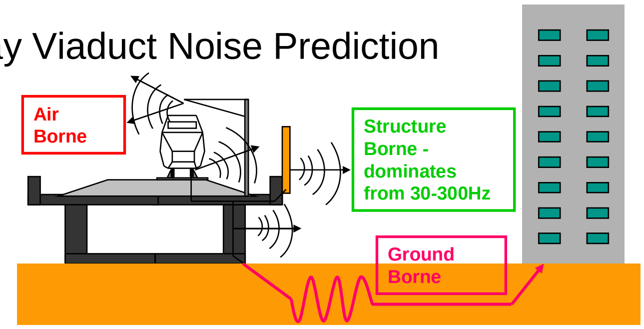
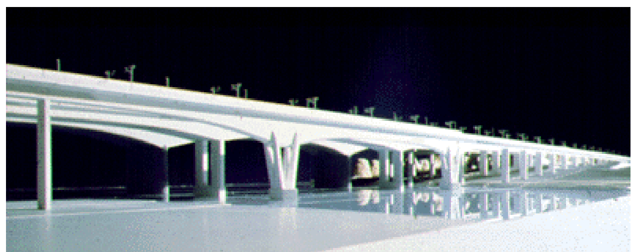
Railway Viaduct Noise Prediction





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Reasons for analysing the bridge noise

- Government limits for new bridges, e.g. 65dB at nearest house
- Noise-reducing measures can be added to the railway but these are expensive
- What is the cheapest solution that meets the target?
- Usual methods cannot show this - they only compare which design is quietest.
- We developed a new method with LS-DYNA.

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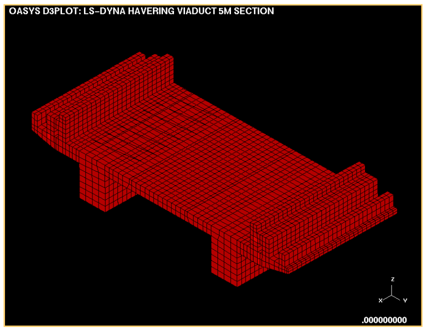
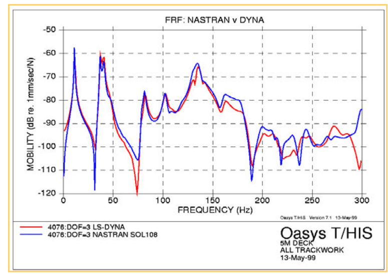
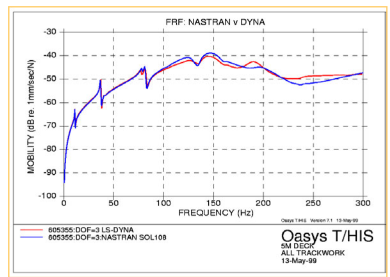
Checking LS-DYNA vibration vs NASTRAN

- Solid elements (ELFORM=2) and shell elements (ELFORM=16)
- *DAMPING_FREQUENCY_RANGE gives nearly constant damping across a range of frequencies (in this case 30-300Hz).







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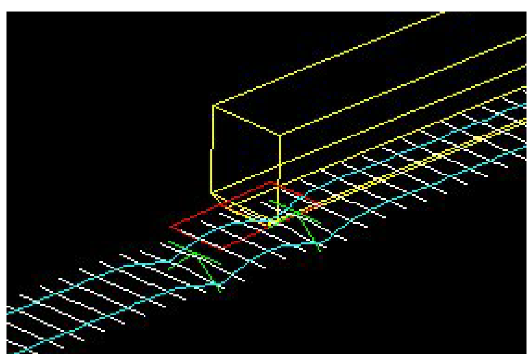
*RAIL_TRACK and *RAIL_TRAIN

- Wheel to rail contact condition
- Surface roughness included
- Vertical and lateral stiffness



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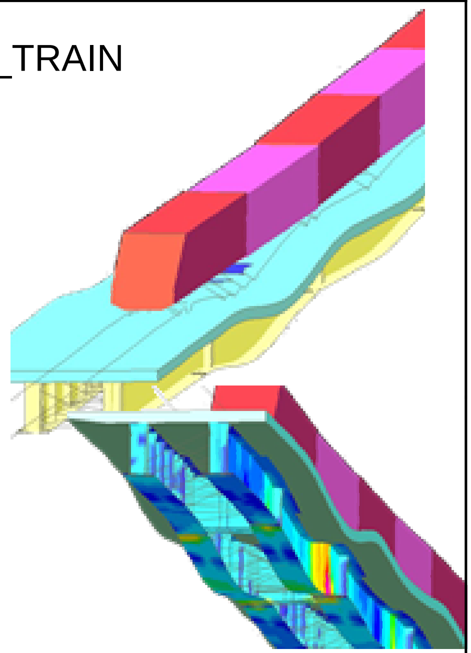
*RAIL_TRACK and *RAIL_TRAIN

*RAIL_TRACK and *RAIL_TRAIN define a contact condition between the wheels and the rails, including option for surface roughness (curve of surface height versus distance along track).

The train model includes suspension.
The track model includes rails, sleepers, pads and ballast. These are modelled with beam, spring and damper elements.

This picture shows a study of stresses and forces arising from a moving train. Vertical deflections are magnified. The movement of the wheel forces may induce a dynamic response of the bridge.



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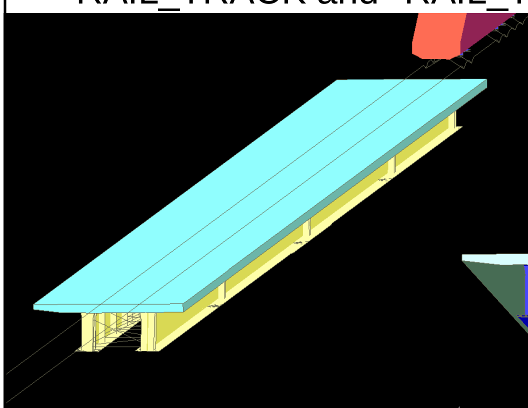
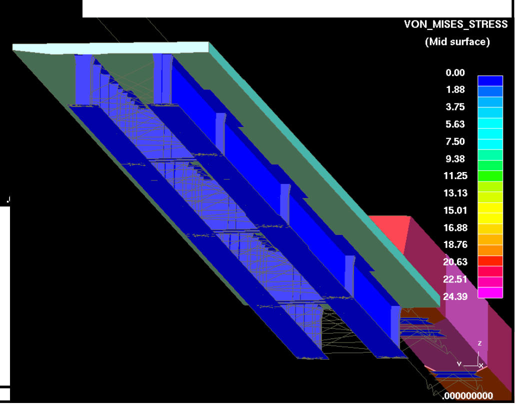
*RAIL_TRACK and *RAIL_TRAIN typical application



(Vertical deflections magnified)



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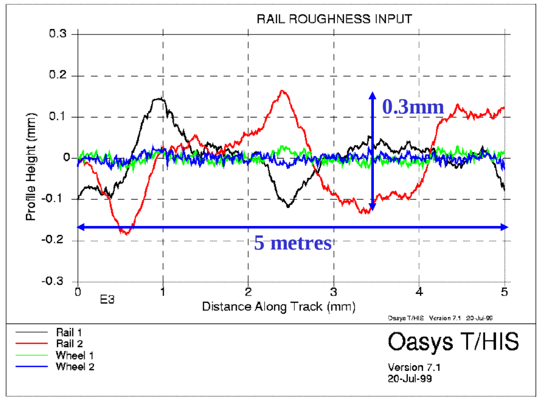
Using *RAIL to model vibration

- Most important source of structure-borne vibration is rail roughness, even though the roughness is very small
- Input data for model was measured on high-speed rails
- Roughness curve is an input on *RAIL_TRACK (rails) and *RAIL_TRAIN (wheels)



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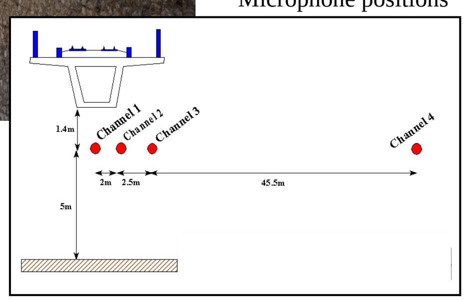
Viaduct used for correlation

Microphone positions



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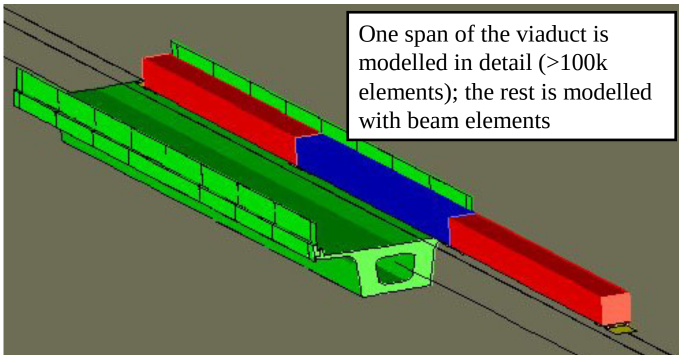
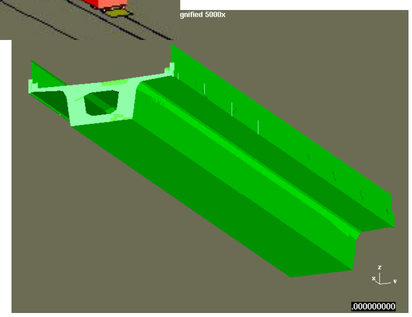


LS-DYNA model of train crossing concrete viaduct



Response of viaduct (magnified)

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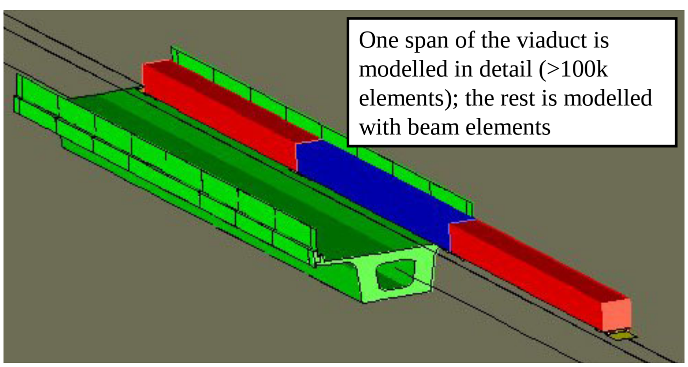

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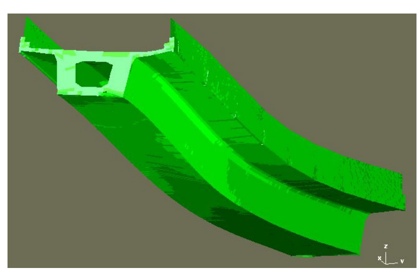

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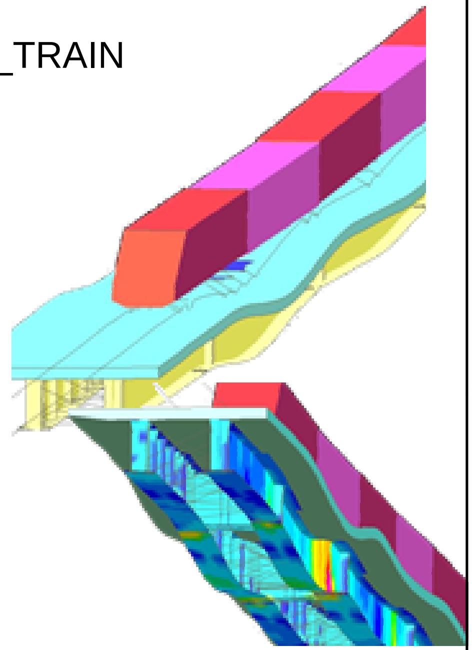

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Notes about modelling technique

- We used LS-DYNA to calculate the vibration of the structure
- Should we use brick elements to model the vibration in the air? (noise):
  - At that time, coupling of the structure to the air mesh did not work well for vibration problems.
  - The number of brick elements would be > 1 million.
  - Boundary element technique was more appropriate for this problem

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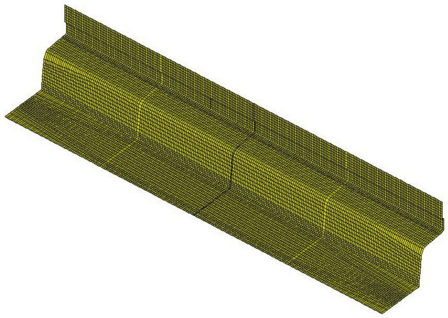
Noise prediction method



Train, track and viaduct model

LS-DYNA

Velocity time histories at nodes

Oasys T/HIS

Velocity vs frequency at nodes

Boundary element model of surface of viaduct → LMS SYSNOISE

Sound pressure vs frequency

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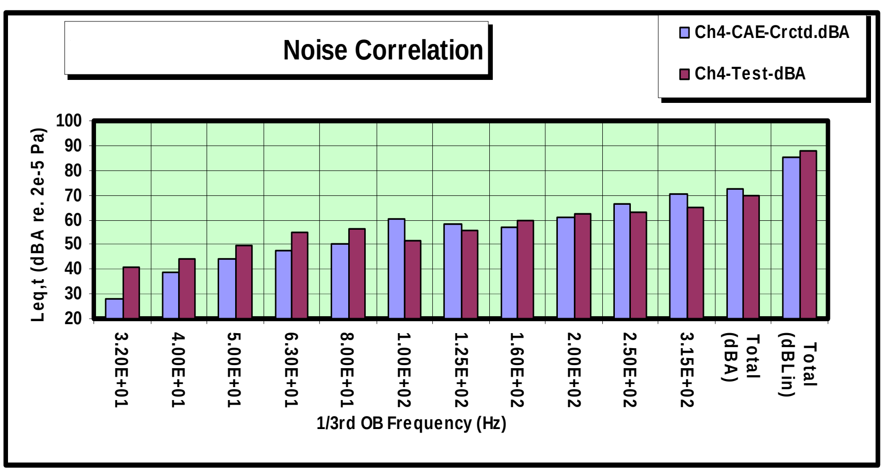
Correlation of predicted noise



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Conclusion from Railway Viaduct Noise Prediction

- Absolute noise levels are well predicted
- We used this method to predict the noise from new bridges. Then we could choose the cheapest design with acceptable noise levels.
- Traditional frequency response analysis would only show which design is quietest (A to B comparison)

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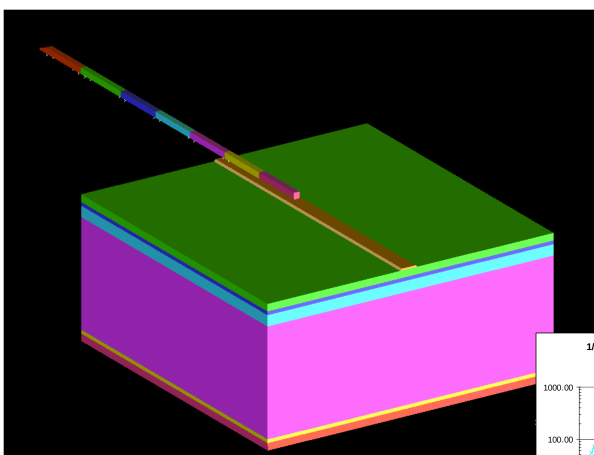
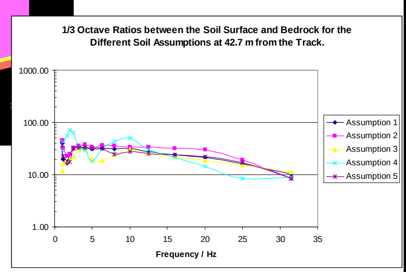
Ground-borne vibration



- Method now being developed



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Conclusions of Paper

- LS-DYNA can be used successfully in civil engineering design, often in situations where other codes fail. Run times are shorter than competing codes for large 3D problems, even quasistatic problems.
- New capabilities have been added to increase the range of applications - these will be included in LS970.
- All of the applications shown used the explicit solution method. In future, implicit capabilities of LS-DYNA may be used for civil engineering applications, e.g. initial gravity loading.

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