DEVELOPMENTS IN HIGH-SPEED TRACK DESIGN

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Summary

Presently high-speed tracks are built on a large scale. Although ballasted tracks are still popular, more and more slab tracks are constructed. They have some significant advantages such as low maintenance, high availability, low structure height, and low weight. The main emphasis of this paper is on the application of non-ballasted concepts for high-speed operation. Special attention is given to slab soil interaction and optimization with respect to bearing capacity.

Keywords: High-Speed Tracks, Slab Track Design, Slab-soil interaction

1 Introduction

With the design of railway lines factors like life cycle cost, construction time, availability and durability play an increasingly important role. In this respect non-ballasted track concepts offer good opportunities. Especially with high-speed operation wave propagation under train velocity is an important factor, in particular in delta areas with relatively weak subgrades. This often makes it necessary to decide for slab track, as for instance was the case in The Netherlands for the High-speed Line South.

With the growth of traffic intensity it becomes more and more difficult to carry out maintenance and renewal work. In The Netherlands night time possessions often last no longer than 5 hours, and on the future high speed line in Korea (435 km from Seoul to Pusan) the maximum effective possession is estimated at no more than 1 ½ hours per night. In this respect the current increase in popularity of low-maintenance track designs is not surprising.

In the past new projects were mainly assessed on the basis of in-

Figure 1 Ballasted high-speed track (Korea)

vestment costs, whereas today the principle of life cycle costing is strongly emerging. Although ballasted concepts are still widely used in high-speed operation (Figure1), they will loose attractiveness in favour of slab track systems due to this new attitude.

2 General considerations

Presently all over the world non-ballasted track concepts are being applied, although still at a moderate volume. The great advantages of such structures can be summarized as follows:

- Reduction of structure height;
- Lower maintenance requirements and hence higher availability;
- Increased service life;
- High lateral track resistance which allows future speed increases in combination with tilting technology;
- No problems with churning of ballast particles at high-speed.

If the low-maintenance characteristics of slab track on open line are to be retained, great care must be taken to ensure that the subgrade layers are homogenous and capable of bearing the loads imposed. The slabs may be prefabricated or poured on site. The high level of investment required has prevented widespread use of slab track on open line so far. However, on the basis of life cycle costs a different picture is obtained [1]. The greatest savings will be achieved in tunnels and on bridges. The use of more efficient construction methods, of the type used in the road construction industry, could reduce construction costs still further.

3 Design principles

Generally speaking there are two ways of designing slab track. According to the German school, based on highway design, the supporting layer should have a substantial bearing stiffness, represented by the modulus of elasticity Ev2 ≥ 120 N/mm^2. This requirement refers in particular to slabs on a subgrade and is originated by the fact that incoherent block structures, having no bending resistance, could be used. This requirement also covers the condition that no differential settlements may occur. Slabs designed in this way only contain reinforcement in the neutral axis to control crack width in the concrete. This is standard practice in Germany. On engineering structures like bridges and tunnels, providing rigid supporting conditions, this is a logical solution. However, when slabs are built on subgrades often massive soil improvements are required, which make slab tracks financially unattractive.

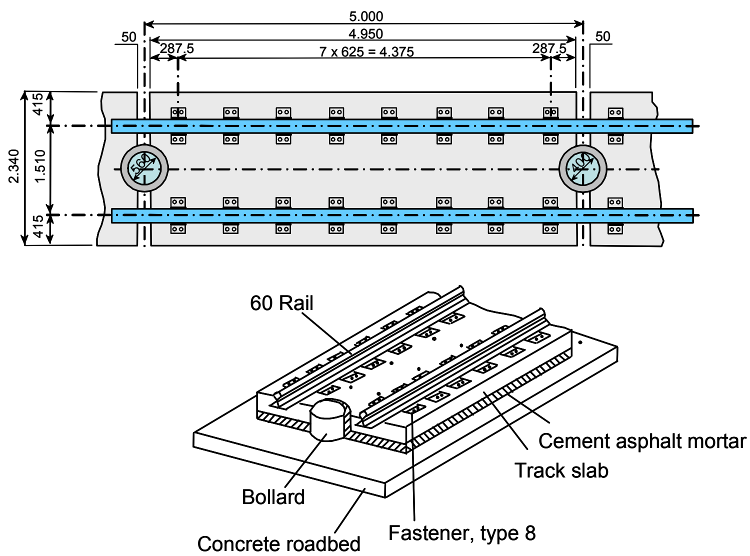

Figure 2 Shinkansen slab

The second way of constructing slabs, especially on soils where some settlements may be expected, is with reinforcement at the top and at the bottom of the slab to take bending stresses and axial forces. Various studies at TU Delft have shown that relatively high reinforcement percentages of about 1.5 % for a B35 concrete [2, 3, 6]. On the other hand only very limited soil improvements are necessary.

If no bending resistance is required also prefabricated slab sections can be used. On bridges this has the advantage that the influence of bending of the bridge has no influence on the bending stresses in the track slab.

If (semi) continuous slabs are applied the construction method can consist of either pouring the concrete into a casing, or constructing continuously using a slipform paver. The price is to a large extend determined by the building efficiency.

Especially for slab tracks it is important to control the track geometry carefully during construction, as corrections afterwards are difficult. Perhaps even more important is to make the welds at very tight tolerances to avoid impact loads which have a strong negative influence on the service life of the entire structure.

4 Non-ballasted systems in use

Japan was effectively the birthplace of high speed rail. Development work on the Shinkansen network started at the end of the 1950s, and the first line (between Tokyo and Osaka) opened in Autumn 1964. Five lines are currently in service and a sixth is under construction. Government plans dating back to 1970 specify a national Japanese high speed network of 3 500 km of double track. By 1993, a good 1 400 km of this had been built (double track), of which more than 1 000 km consists of ballastless double track. In Japan, ballastless track always consists of prefabricated slabs just under 5 m long. The percentage of ballastless track varies considerably from line to line. The newer lines include a higher percentage (up to 96 %). The slab track design has remained virtually unchanged since the first sections were laid in 1972.

The Shinkansen slab track (Figure 2) consists of a sublayer stabilized using cement, cylindrical “stoppers” to prevent lateral and longitudinal movement, reinforced prestressed concrete slabs measuring 4.93 m x 2.34 m x 0.19 m (4.95 m x 2.34 m x 0.16 m in tunnels) and asphalt cement mortar injected under and between the slabs. The slabs weigh approximately 5 tonnes.

Ballastless track was undergoing rapid development in Germany. Since 1996, DB has been operating a test track in Karlsruhe consisting of seven new types of ballastless track. The best-known German designs is the Rheda system. There are numerous variants which indicates that

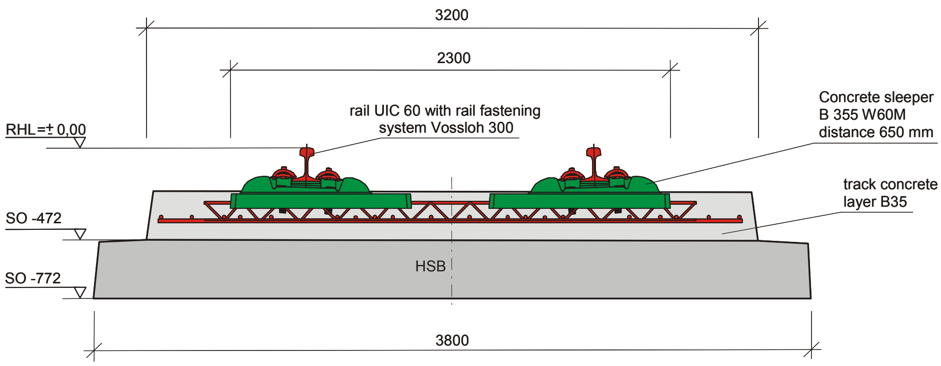

Figure 3 Rheda 2000

the initial designs were not completely successful. The most developed Rheda system is Rheda 2000 [7]. By eliminating the conventional concrete trough, a significant simplification of the overall system configuration was achieved. As a result, the entire cross section of the slab has become one monolithic component. Due to the elimination of the trough and the use of twin-block sleepers, a considerable reduction of the structural height could be achieved as is revealed by the dimensions in Figure 3.

In Germany a prefabricated slab track system, produced by Bögl, is in use. This system is largely similar to Shinkansen slabs except that the Bögl slabs are made of B55 steel fiber reinforced concrete and are 20 cm thick, 6.45 m long, and 2.55 or 2.80 m wide. The slabs are pre-stressed in lateral direction; in longitudinal direction traditional reinforcement is applied. Spindles integrated in the slabs provide an easy and quick adjustment of the slabs (Figure 4). The slabs are connected longitudinally by post-tensioned steel rods in the neutral axis.

The infrastructure of the High-Speed Line South (Netherlands) is built according to a so-called DBFM contract (Design, Build, Finance, Maintain) and was awarded to Infraspeed, a consortium comprised of Fluor Daniel, Siemens and Koninklijke BAM Groep. In this contract the availability of the infrastructure is guaranteed at a specified level for 25 years. The track consists of a low viaduct consisting of a piled concrete slab, with on top a separate slab with Rheda 2000 track. Both supporting structure and Rheda slab are dilated at intervals of 35 m to limit the longitudinal forces in the concrete and the displacements at the end of the structure. The vertical relative displacements between the substructure elements at the expansion should be confined to 2 mm.

The French Stedef system is most often used in tunnels, especially for metro systems. However, the technique is also used on high speed networks. A rubber boot under the sleeper provides a high degree of elasticity, which ensures good noise and vibration insulation. The Sonneville Low Vibration track is closely related to the Stedef system. This is a block track design, which, like Stedef, also uses a rubber boot. Applications include the Channel Tunnel. Another twinblock variant related to Stedef is the Swiss Walo system, mainly used in tunnels. A special slipform paver lays a concrete slab, following which the sleepers – fitted with rubber boots – are placed in position and cast into place.

The Edilon block track system (Figure 5) falls into the same category, and is mainly used for bridges and tunnels. Under this (top-down) system, the first step is to place the rails and blocks in position. The blocks are then cast in using Corkelast, to provide the necessary elastic support. Important applications include 100 km on Prorail, the Dutch Infra company, and on light rail systems in the Netherlands and approximately 100 km on Madrid metro.

In Italy ballastless track has been used on a very limited scale. In 1992, FS had less than 100 km of ballastless track, of which 2 × 5.4 km were located on the Rome-Florence high speed line. This track, supplied by IPA, is based on the Japanese system mentioned above.

Figure 4 Bögl slab track system

5 Embedded rail structures

All the designs mentioned so far were based on the rail being supported at discrete points – the sleeper principle. Since 1976, a continuously supported rail system has been in use in the Netherlands on a small scale. The system is known as the Embedded Rail Structure (ERS), and involves providing continuous support for the rail by means of a compound consisting of Corkelast (a cork/polyurethane mixture). The great advantage of this design is that the track is built "top-down", which means that tolerances in the supporting structure have no effect on the track geometry obtained. Another major advantage is that the wheel does not experience any difference in vertical stiffness like in sleepered track. This stiffness difference is one of the major sources for the development of corrugation [8].

Figure 5 Edilon block system

Prorail has over 20 years experience with this system, and it has proved to require little maintenance. Figure 6 illustrates the cross section of a 3 km slab track section near Best in The Netherlands which was built in 1999.

The traditional ERS concept still contains the conventional UIC 54 rail. However, an optimized rail concept had been developed in 1998, as depicted in Figure 7. This SA42 rail is capable of carrying 225 kN axle loads and produced 5 dB(A) less noise. An additional advantage is the substantial reduction of polyurethane. This new rail concept was installed in the previously discussed test track near Best over a length of 150 m.

A similar low noise solution was proposed by Balfour Beatty [9]. In this case too a block rail is applied to achieve improved acoustic properties and low structure height. This so-called BB Embedded rail is depicted is Figure 8. The block rail, together with pad and shell is positioned and this assembly is then grouted into the concrete. An advantage is that the rail can be replaced afterwards relatively easily.

The examples so far pertained to concrete. A new development in The Netherlands is an embedded rail structure in asphalt pavement, referred to as ERIA (Embedded Rail In Asphalt) [10]. This is a special solution for trams and light rail in urban areas. This silent rail structure is integrated into the total pavement, including crossings.

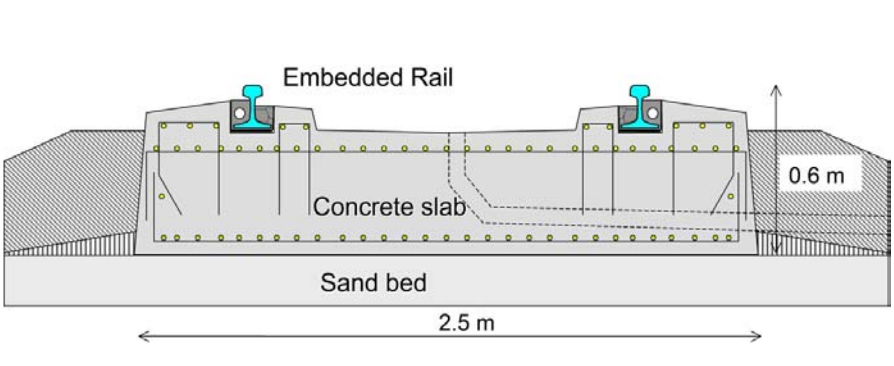

Figure 6 Embedded rail track near Best (NL)

Two variants will be tested: The embedded rail prefabricated in a steel trough, which is fixed into a combi-layer of very open asphalt concrete, filled up with a cement slurry.

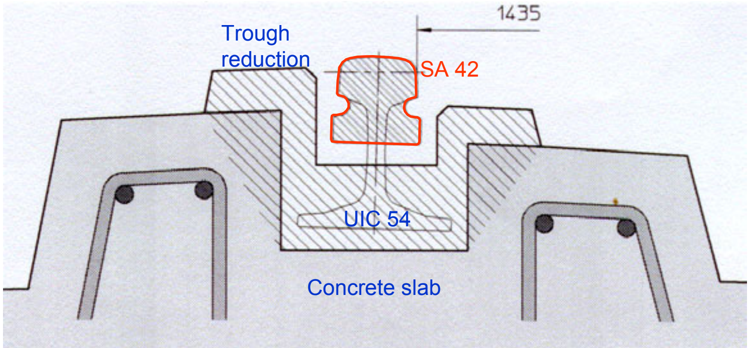

Figure 7 Low-noise SA 42

In the second variant the bitumen in the upper 10 cm has been replaced by the much stronger polyurethane to replace the steel trough. Finite element calculations showed that these measures were necessary to withstand in particular the transverse wheel loads of trucks. Figure 9 shows a test set-up at TU Delft for the polyurethane variant. In addition to the low noise and vibration nuisance the major advantage is short construction time. After the completion of a large testing program at TU Delft an in situ test at HTM The Hague is envisaged later in 2003.

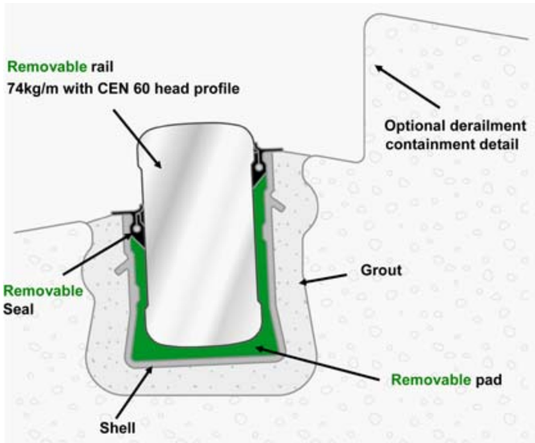

Figure 9 Balfour Beatty embedded rail

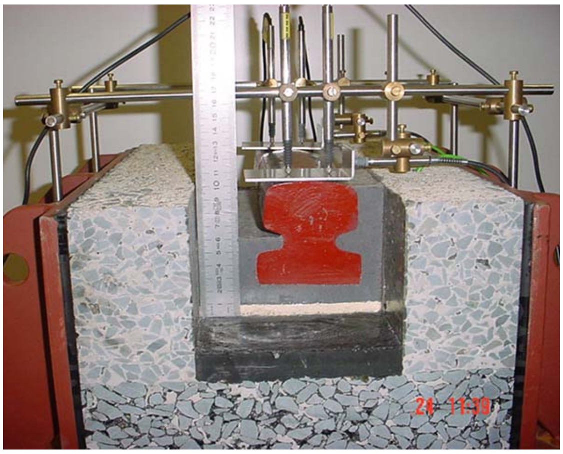

Figure 8 ERIA polyurethane variant

6 Slab optimization

As discussed earlier the reinforcement in most of the slabs is applied in the neutral axis just for crack control purposes. An alternative design for slab track, based on Rheda 2000, has been suggested in [6] (Figure 10). In that design reinforcement is applied at the top and at the bottom of a slab to create both bending resistance and crack control. Due to the significant bending stiffness of the slab less supporting stiffness of the foundation (soil) is then required and so substantially less soil improvements would be necessary.

In [11] it has been shown that a typical reinforcement degree of 1% used in concrete slabs on improved (high quality) soil is not applicable on soils of moderate or bad quality (according to the German standards [1]). Therefore, in the optimization of a slab track a reinforcement of 1.2 % and 1.5 % have been used.

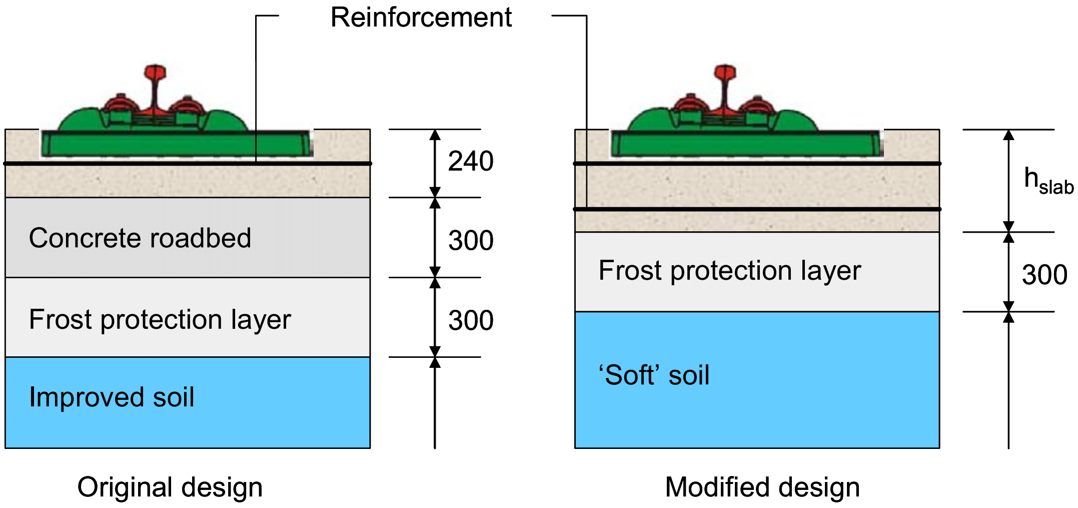

Figure 10 Original Rheda verses modified design

At TU Delft various studies have been carried out for slab design under dynamic train loads [4] in relation to reinforcement percentage, bearing capacity of the soil and cost. In these analyses use was made of the MARS (Multipoint Approximations based on Response Surface fitting) optimization method [5].

To analyze the dynamic behaviour of a slab track a finite element model implemented in RAIL program have been used [4]. Using the model the structural responses such as displacements and stresses in slab and foundation due to a moving track load have been obtained.

The total cost of of a slab track structure can be reduced by decreasing the efforts related to soil improvement. By increasing the bending stiffness of the slab, the stiffness of the soil layer required for safe track operation can be reduced, which means that softer soil are acceptable. The stiffness of a slab can be increased by for example increasing the height of the slab. On the other hand, by increasing the thickness of the slab and reducing the stiffness of the foundation, the stresses in the foundation are increasing. To satisfy the safety requirements the vertical stiffness of the foundation should be increased which increases the total cost of the design.

To optimize the slab track parameters, one can try to vary the thickness of a slab in order to reduce the stiffness of the supporting layer (which is proportional to the soil improvement costs), while satisfying the constraints on the maximum allowable stresses in the slab [3] and in the foundation. A series of optimization problems for various slab thicknesses have been performed. The results are shown in Figure 11.

From this figure it can be seen that a slab with a reinforcement of 1.2 % and thicknesses of 30 - 35 cm requires a substantial soil improvement (the foundation modulus should be greater than 0.11 N/mm^3, or Ev2 > 100 N/mm^2). On the other hand slabs with the thicknesses of 40 to 50 cm can be applied on soil of moderate and even poor quality, with C > 0.05 N/mm^3, or Ev2 > 30 N/mm^2. If a reinforcement percentage of 1.5% is used then the slab thickness can even be reduced to values in the order of 30 cm.

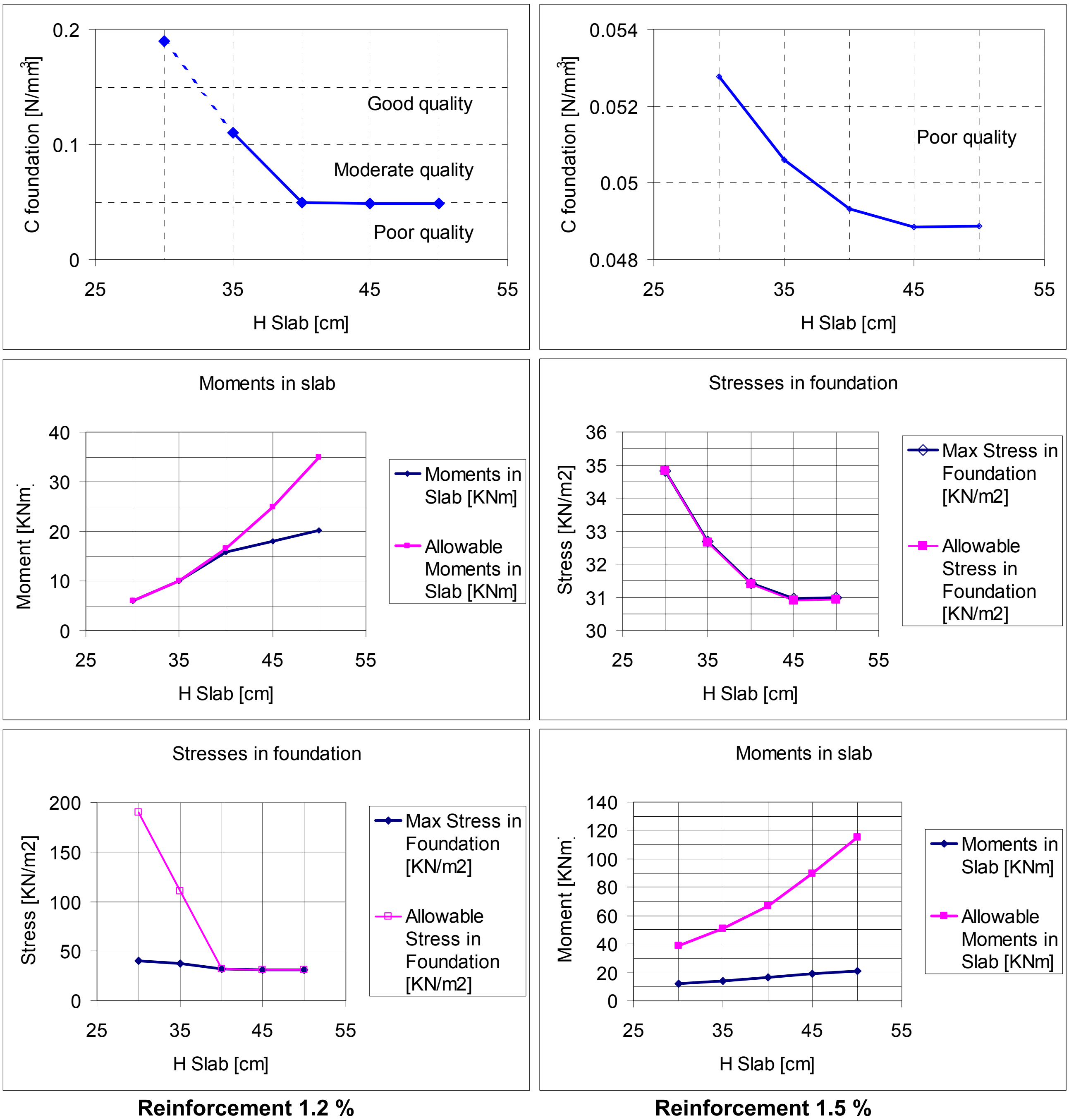

Figure 11 Results of slab track optimisation

7 Outlook

From a point of availability, life cycle management and constraints due to Rayleigh waves the application of slab track may be expected to grow, especially in high-speed operation. Efficiency of constructing will play an essential role. In this respect slipform paving seems to have obvious advantages. On subgrades slabs with a bending resistance are potentially more cost-effective. Further studies to the effects due to subgrade settlements would be necessary to further optimize the slab soil interaction.

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