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Experimental investigation of soil-structure interaction for the transition slabs of integral bridges

This paper presents the results of an experimental test series carried out to investigate the soil-structure-pavement interaction in the vicinity of the transition slab at the end of an integral bridge. The main function of transition slabs is to ease the transition between the bridge deck and the embankment in the case of differential settlement. Additionally, in the case of integral bridges, transition slabs can solve the problem of moderate imposed longitudinal deformations at the bridge ends. In this case the displacements imposed on the transition slab can lead to vertical and longitudinal surface displacements and to cracking of the pavement. Based on the observed behaviour, some recommendations are proposed for the geometry and surface conditions in order to optimize the behaviour of transition slabs.

Keywords: transition slab, approach slab, integral bridges, pavement cracking, soil-structure interaction, soil-structure-pavement interaction, large-scale testing, bridge abutments

1 Introduction

In many countries, bridges represent an important component in the road infrastructure. Those bridges must be kept in good condition while minimizing the cost of interventions. It was in that context that the concept of integral bridges was introduced in the 1990s. Integral bridges are monolithic structures, built without expansion joints and often without mechanical bearings [1], [2], [3], [4]. This leads to a lower lifetime cost because the initial construction costs are lower and because there are no mechanical devices, which require periodic inspection, maintenance and, occasionally, replacement. Furthermore, by avoiding expansion joints, which often leak and can initiate damage to the bridge and its infrastructure, the number of maintenance interventions can be drastically reduced. Over the past two decades, a large number of integral bridges with increasing lengths have been built and their performance is, on the whole, satisfactory.

As there are no expansion joints, the movements of the bridge superstructure need to be directly transferred to the surrounding soil. For very short bridges (up to 20 m), this can be easily accommodated without a transition slab (or approach slab). For longer bridges, a transition slab is used to accommodate the larger movements occurring at the bridge ends, avoiding the formation of transverse bumps and dips as well as cracking of the pavement. In these cases, bridge design guidelines typically limit the maximum length of integral bridges to 60–90 m [1], [2] or, more precisely, limit the maximum displacement at each bridge end [5], which is more appropriate, particularly in the case of existing bridges where long-term deformations have ceased to increase. For longer bridges, indeed for larger movements at the bridge ends, solutions with expansion joints are required.

In order to be able to increase the maximum length for integral bridge applications, there is a need for a better understanding of the behaviour of the soil-structure-pavement combination in the zone surrounding the transition slab. This paper presents the results of a series of large-scale tests focusing on the soil-structure-pavement interaction in the vicinity of the transition slab at the bridge end. Longitudinal and vertical displacements of the pavement surface and cracking of the asphalt were observed and measured.

2 Integral bridges

Fully integral bridges are built monolithically, without any mechanical devices between the various elements of the bridge – piers, abutments, deck and transition slabs (Fig. 1a). In this type of bridge, relatively large forces caused by the earth pressure and cracking due to imposed deformations may arise in the abutment wall when the bridge expands or shortens. Constructional solutions have been proposed to increase the flexibility of the abutments of integral bridges or to decrease the earth pressure behind them [5], [10], [16], [17], [18], [19].

Semi-integral bridges are bridges in which the bridge superstructure and the transition slab are monolithically connected and sliding bearings are placed at the top of the abutment wall (Figs. 1b and 1c) [2], [3]. This configuration decreases the forces acting on the abutment wall while preserving the advantage of a structure without expansion joints at pavement level. Conversions of existing bridges with expansion joints into semi-integral bridges are possible and are illustrated in Fig. 1d.

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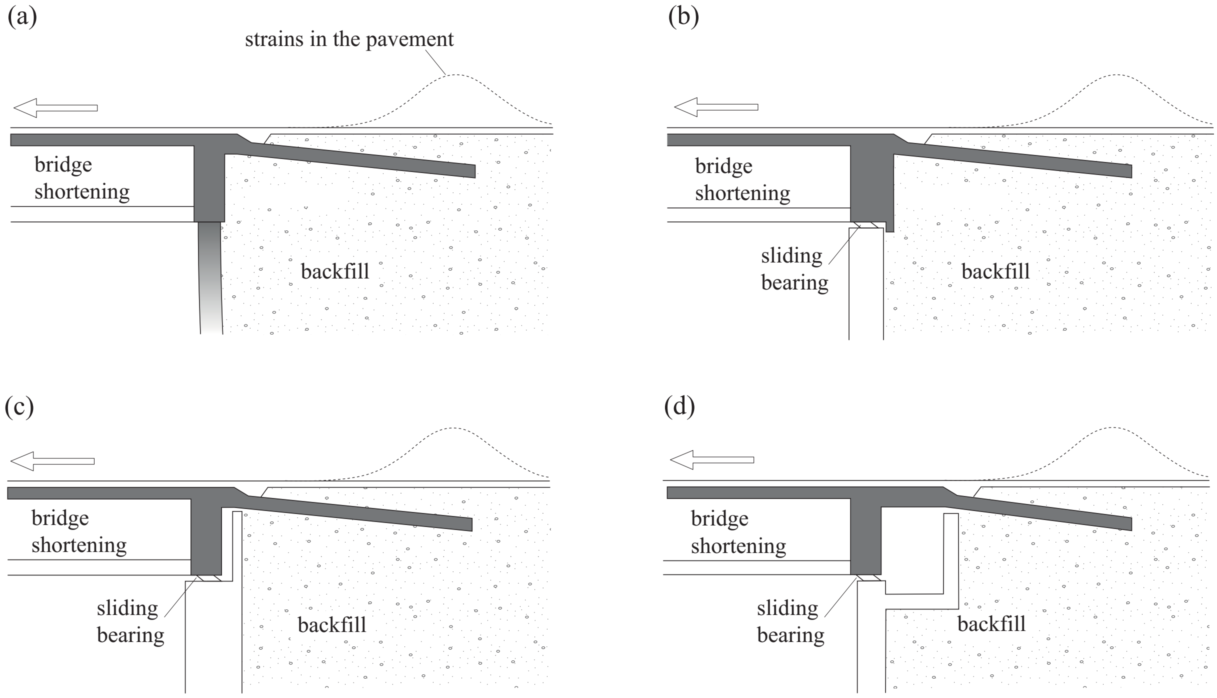

Fig. 1. Bridge ends of integral bridges; dark areas are displaced when bridge shortens: a) fully integral bridge, b) and c) two solutions for a semi-integral bridge (abutment wall does not move), d) conventional bridge with inspection chamber transformed into a semi-integral bridge

Whereas integral bridges have been the subject of a large number of publications in past decades, there has been – to the authors' knowledge – very little laboratory testing of representative configurations of transition slabs. Most publications on this subject are either of an analytical nature [6], [7], [8], [9] or are based on field measurements of the actual performance of recently built integral bridges [10], [11], [12]. A few authors report on the actual behaviour of the road surface in service [3], [13], [14], [15].

The aim of the analytical research reported in [6] was to discover the maximum length possible for a bridge built without expansion joints, without detrimental effects on its behaviour. The main criterion used in the study was limiting the perceived effect of the surface bumps or dips at the end of the transition slab. One of the conclusions was that a large buried depth at the end of the transition slab has a favourable effect on limiting the amplitude of the surface discontinuities.

3 Transition slabs

3.1 Functions of transition slabs

The main function of a transition slab is to ease the transition from the relatively soft embankment to the stiffer bridge superstructure, limiting the discomfort to users due to differential settlement [20]. Transition slabs span over the part of the embankment that is located in the immediate vicinity of the abutment wall and is thus typically less well compacted. They also limit the earth pressure induced by traffic on the abutment wall. In bridges with expansion joints, transition slabs are connected to the abutment back wall, which does not move with the bridge, the bridge's longitudinal movement being taken by the expansion joint (Fig. 2a).

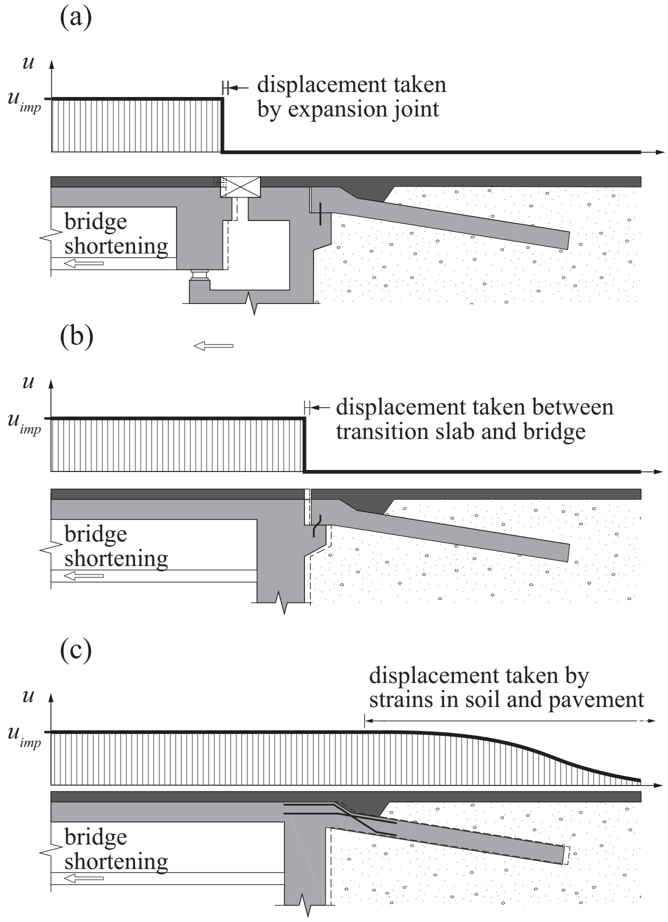

Fig. 2. Typical bridge ends and transition slabs and corresponding longitudinal displacements u at surface of pavement: a) bridge with expansion joint, b) integral bridge with non-moving transition slab, c) integral bridge with moving transition slab

The abutments of integral bridges need to be designed to absorb the longitudinal displacements normally accommodated by expansion joints. The back wall of the abutment is connected to the bridge and moves with it. If the transition slab is connected to the abutment wall in a flexible manner, it will not move with the bridge and the longitudinal movement of the bridge will be taken up at the location of the connection (Fig. 2b). To avoid a crack forming in the pavement at this location, some kind of joint needs to be inserted in the pavement, e.g. an asphaltic plug system made of polymer-modified asphalt. This is in fact another type of expansion joint, with a need for inspection and a potential for leakage.

If the longitudinal connection between the bridge and the transition slab is rigid, the two elements will move together. As the movement of the pavement further away from the bridge is zero, the longitudinal movement of the bridge will be distributed over the length of the transition slab, inducing longitudinal strains in the pavement (Fig. 2c). In this case the transition slab also has to distribute the effect of the bridge movements to the soil and the pavement.

3.2 Buried transition slabs

The present article focuses on buried transition slabs, which are covered by a layer of compacted sand and gravel and an additional asphaltic pavement layer, continuous from the embankment zone to the bridge (Fig. 1). This detail is common in several European countries [4], [5]. In other countries, and in several US states in particular, the traffic rides directly on the concrete surface of the bridge, and the transition slab is horizontal, the continuation of the surface of the deck, with a construction detail between its end and the pavement over the embankment (again, some kind of joint) [21], [22].

3.3 Solutions for the design of transition slabs for integral bridges

Several parameters need to be considered when designing transition slabs for integral bridges. They correspond to multiple, sometimes conflicting, goals, such as limiting the cost of construction, the cost of maintenance and maintaining the comfort for users.

As mechanical devices of all kinds are more costly than concrete elements, the fundamental solution for integral bridges is to **avoid expansion joints and mechanical bearings**. The term "jointless" has sometimes been associated with this type of construction. This can be somewhat misleading because if there is no joint in the bridge itself, there can be joints at other locations, e.g. at either end of the surface transition slab, as already mentioned [17], [21], [22].

An efficient solution to these problems is to use a **moving buried transition slab**, which can be protected by a waterproofing membrane and is covered by backfill and the asphalt pavement layer [3], [4], [5], [23]. This solution has two advantages: with a monolithic connection between the bridge and the transition slab, uncontrolled cracks in the pavement close to the abutment wall (Fig. 2b) can be avoided, and, secondly, at the far end of

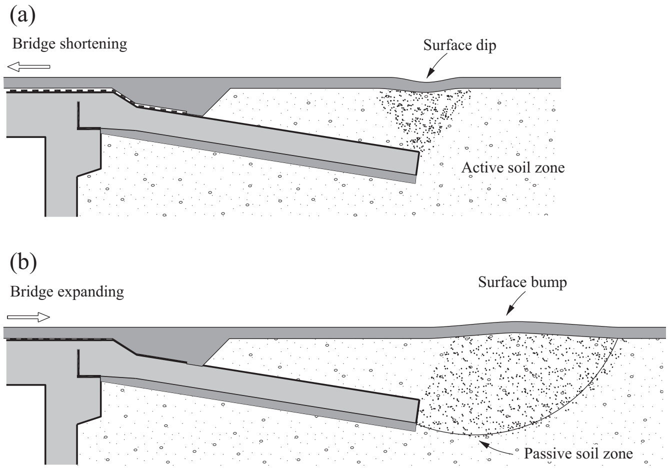

Fig. 3. Potential deformations of pavement: a) dip due to bridge shortening, b) bump due to bridge expansion

the transition slab, the longitudinal displacements can be distributed over a sufficient length to limit surface strains in the pavement and related cracks. It also helps to distribute the strains in the soil, which can lead to the formation of transverse surface dips when the bridge contracts, or bumps when the bridge expands, which reduce the comfort of the ride (Fig. 3) [6].

Transverse cracking of the pavement caused by longitudinal movements of the transition slab should be avoided. In the configuration shown in Fig. 4a, when the bridge shortens, the transition slab moves with it, but the soil above it slides and does not move, along with the pavement. This results in local cracking occurring near the bridge end of the transition slab, which are unfavourable. In the configuration shown in Fig. 4b, the soil and the pavement above move together with the transition slab. For large values of bridge shortening, the pavement cracks at the far end of the transition slab. Although this is not ideal,

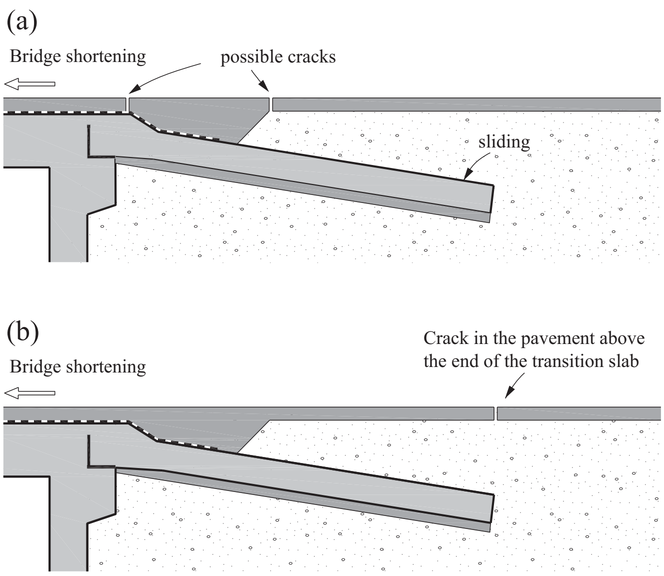

Fig. 4. Potential cracking zones in pavement: a) close to bridge end, due to soil sliding on transition slab for case of transition slab with smooth top surface, b) at end of transition slab for a rough top surface to slab

this location is less unfavourable as the potential for aggressive water from the pavement reaching the bridge structure is lower. Some authors report on measures to improve the soil above the transition slab by inserting geotextile layers [24]. Using a pavement with a larger deformation capacity above the transition slab is also an option.

4 Objective of the research

The objective of the research was to investigate how displacements of the transition slab affect the surface of the pavement by means of a large-scale test setup. In particular, the influence of the buried depth at the end of the transition slab was varied in order to assess the conclusion by *Dreier* [6] that an increase in the buried depth allows for larger bridge movements.

4.1 Bridge movements

Temperature variations are an important cause of longitudinal displacements in all types of bridge. For concrete bridges, shrinkage causes shortening of the bridge, as does creep in prestressed concrete bridges [8], [9], [10]. On one side the amplitude of the displacements at the bridge end is proportional to its distance from the fixed point; on the other side it is proportional to the total longitudinal strain resulting from temperature, shrinkage and creep [6]. Although the temperature of the bridge changes constantly, the amplitude of daily longitudinal movements is clearly smaller than that of the seasonal cycles.

4.2 Pavement strains

Whereas strains in the pavement on the bridge are typically very small and can be easily accommodated, the situation is different near the bridge ends, where the total displacement at the bridge end is distributed over a relatively short length. This may lead to very high strains in the pavement and in the soil over the transition slab.

5 Test setup and testing procedure

5.1 Test setup

The test setup was conceived to represent closely the zone around the transition slab as it is often built for Swiss and European highway bridges [5]. The large scale of the test (about 2/3 scale) allows the test results to be directly transferred to actual designs. The test report [25] gives all the details of the project. The amplitude of the applied displacements (up to more than 70 mm) was selected to go beyond current limits on displacements for integral bridges [5], [23].

The test setup with a fixed abutment wall reproduces the condition in semi-integral bridges (Figs. 1c and 1d). The case of a bridge with a movable back wall or a movable cross-beam (Figs. 1a and 1b) is not reproduced here. The test setup reproduces the behaviour above and at the far end of the transition slab for all the cases shown in Fig. 1.

Fig. 5 shows longitudinal and transverse sections through the test setup for the second test, which is representative of the series. The test setup was constructed outside of the main laboratory in an open field. During the tests, the setup was covered by a tent to keep the temperature constant. The reaction wall and the testing chamber were built with in situ concrete walls (on the left). The abutment wall was modelled as a 200 mm thick concrete wall. The precast 2.2 × 4.0 × 0.25 m transition slab was placed on a layer of lean concrete, which was itself placed on top of a well-graded and well-compacted road founda-

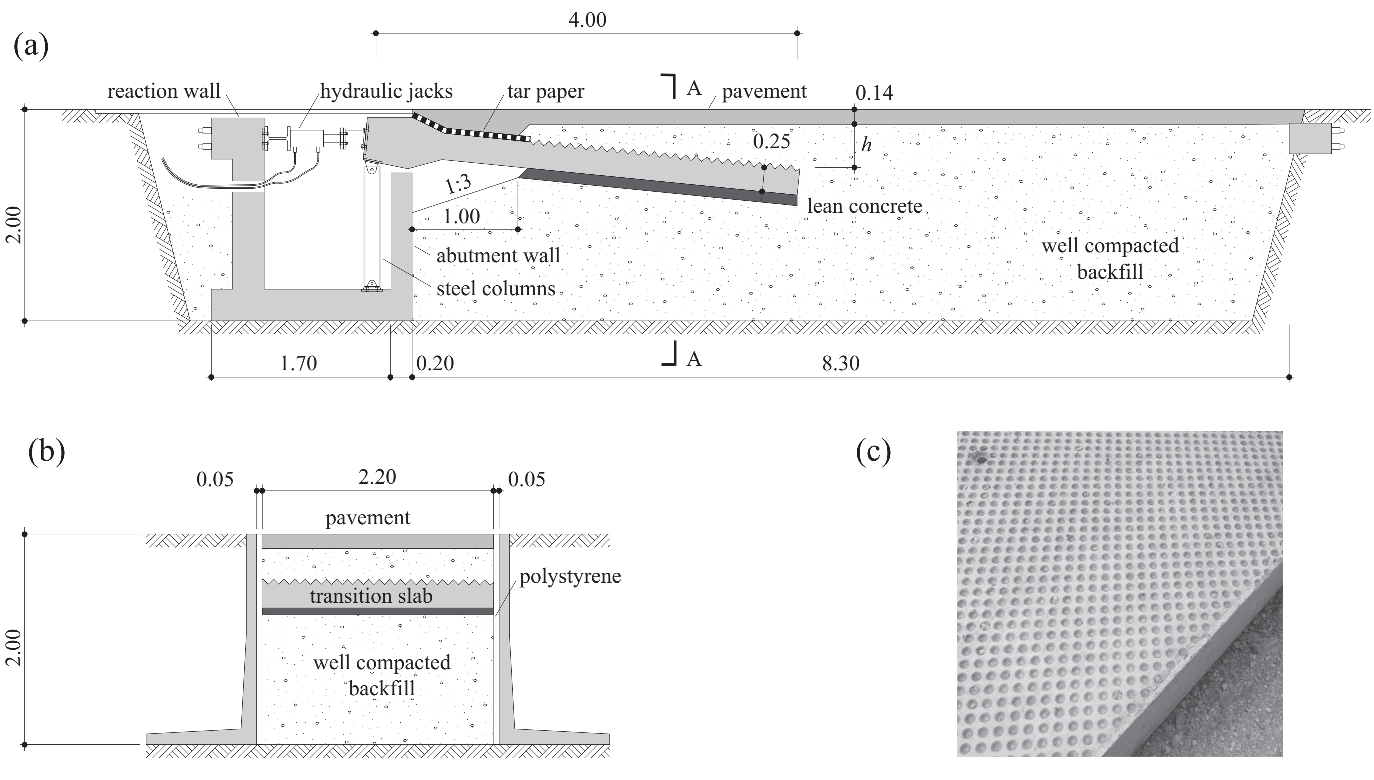

Fig. 5. Setup for TST2 (dims. in m): a) longitudinal section, b) section A-A, c) rough top surface of transition slab

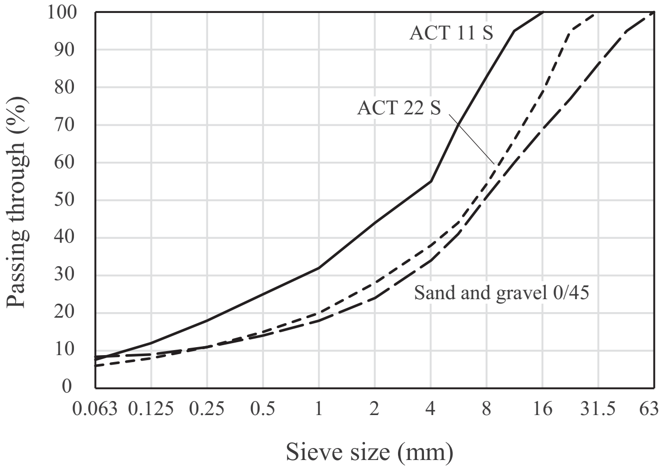

Fig. 6. Particle size distributions for pavement and foundation soil

tion layer (sand/gravel mix, see Fig. 6, typical internal friction angle φ_k = 37°) that extends all the way down to the bottom of the testing pit. Table 1 gives the inclination of the slab for each test. The same transition slab was used for all three tests, as it was undamaged after the first two. In order to be able to model the rough contact surface between the transition slab and the lean concrete, one of the faces of the transition slab was roughened by using a special formwork lining with a depth of approx. 25 mm (Fig. 5c). As that configuration would necessarily leave the surface filled with hardened lean concrete at the end of the test, it was decided to place the rough surface at the top (against the soil) for tests TST1 and TST2 (Fig. 5c) and at the bottom (against the lean concrete) for the last test, TST3.

At its upper end, where it would normally be connected to the bridge deck, the transition slab was supported by two vertical steel columns with top and bottom hinges that allow an approximately horizontal movement, similar to the situation in reality.

Immediately behind the abutment wall, for TST2 and TST3, there is a void in the backfill over a length of 1 m with a slope of 1:3. This was introduced after it was noticed during the first test (TST1) that the abutment wall moved significantly during the pulling phase (bridge shortening), a sign that it was exposed to significant earth pressure. The results from the following tests showed negligible movements of the abutment wall. With a void behind the abutment wall, the behaviour of the soil during pulling for the configurations of Figs. 1c and 1d becomes very similar to that of Figs. 1a and 1b.

The top of the transition slab was designed to represent closely current Swiss design details for transition slabs, with a waterproofing membrane (tar paper glued to the slab) over a length of approx. 1 m, with a thick layer of asphalt on top [5]. A layer of compacted backfill soil and two layers of asphalt were placed over the rest of the slab (90 mm Swiss specification ACT22 S base layer with 4.3 % bitumen 50/70 according to [27] + 50 mm ACT11 S final layer with 5.5 % bitumen 50/70, total thickness 140 mm, see particle size distributions in Fig. 6). The side surfaces consisted of precast L-shaped concrete walls, clad with 50 mm polystyrene to limit lateral friction between the soil and the wall (Fig. 5b). In areas where the hot asphalt would be in contact with the wall, a cladding of two ferrocement plates separated by a plastic sheet was used for same purpose. Sliding of the pavement was observed in the first test, with a maximum amplitude of 6.5 mm at the far end of the test setup in the compression phase. After this test it was decided to roughen the concrete wall in direct contact with the asphalt layer at the far end of the test setup to simulate the fact that, at a certain distance from the bridge, the pavement does not move any more.

5.2 Testing procedure

The transition slab was subjected to loading stages both in the pulling direction (simulating shortening of the bridge superstructure) and in the pushing direction (simulating expansion). A total of three tests were performed, varying the inclination of the transition slab, and thus the buried depth h at the end of the transition slab, the roughness of its top and bottom surfaces and the loading sequence. The main parameters of the study are summarized in Table 1.

Longitudinal displacements were applied to the head of the transition slab through two hydraulic rams with a total capacity of 2 × 400 kN. Monotonic displacements were applied for TST1 and TST2 (pulling followed by pushing) and cyclic displacements for TST3 (pushing followed by pulling for three cycles). More cycles were initially foreseen for TST3, but the fact that a large crack formed at the onset of the first pulling phase made this impractical. Table 1 shows the displacement sequence for all

Table 1. Parameters of the test series

Test	Inclination	Buried depth at end of slab h (mm) (see Fig. 5)	Surface condition top/bottom	Loading sequence	u_{imp} (mm)	Pavement temperature T (°C)
TST1	20 %	950	rough/smooth	pulling pushing	+20, +40, +60, +77 +40, +8, –11, –30	17
TST2	10 %	560	rough/smooth	pulling pushing pulling	+20, +40, +60, +77 +40, 0, –20, –40, –60 –20, 0	20
TST3	20 %	950	smooth/rough	cyclic, pushing, then pulling	1: -20 to +20 2: –24 to +30 3: –30 to +30	5

three tests. The target displacement rate was 1 mm/min. After each displacement step, a series of 20–30 passes with a pneumatic roller with a mass of 20 t were performed to simulate the long-term compacting effect of traffic on the soil-slab-pavement combination.

During the tests, the applied displacement and the corresponding force were monitored continuously, also the rotation of the slab head, the displacement of the abutment wall and the ambient temperature. After each displacement sequence, the displacements in the longitudinal and vertical directions at the surface of the asphalt layer were measured.

6 Test results

6.1 Applied force

Fig. 7 shows the force-displacement diagrams for all three tests. The force required to move the slab was relatively large. Recent findings in [22] show similar and even larger values measured on a bridge in service.

In the pulling phase of TST1 and TST2, the force increased only slightly with increasing displacements. Cracking of the pavement, indicated by a vertical arrow in Figs. 7a and 7b, had a small effect on the applied force. The force necessary to move the transition slab increases with the inclination of the transition slab. In the pushing phase, the force required is significantly larger than in the pulling phase, and it increases steadily with increasing displacement.

Test TST3, with the same transition slab inclination as TST1, was different in several respects: the bottom face of the transition slab was rough, the first loading phase was in compression and the loading was cyclic. The effect of the roughness of the bottom face of the transition slab can be seen in the larger force (compared with TST1) required to move the slab in the tension phase and the increase in that force for increasing displacements. In the pushing phase, the force was comparable with the previous tests but, as will be seen, the behaviour of the transition slab was different.

The force required for the displacement in the pulling phase induces tensile stresses in the transition slab. In all tested configurations, these stresses were always well below the cracking load of the transition slab in tension.

6.2 Cracking of pavement

In all three tests, cracking of the pavement occurred during the first pulling phase, at either end of the transition slab. After initial cracking, the crack opened widely (Fig. 8). Subsequent displacements in the pushing direction partly closed these wide cracks. For tests TST1 and TST2, with the smooth surface of the transition slab underneath and the rough surface on top, the location of the crack was approximately above the far end of the transition slab; the cracks opened for displacements of the slab head of 60 and 35 mm respectively. This is in agreement with *Dreier*'s conclusion that a larger buried depth at the end of the transition slab reduces the influence of the displacements at the surface of the pavement [6]. The displacement at cracking appears to be proportional to the buried depth. It should be noted that a larger buried depth at the end of the transition slab can be achieved by lengthening the transition slab, by increasing its inclination or by starting at a lower point behind the abutment wall.

This makes sense mechanically as the rough top surface of the slab causes the transition slab, the soil and the pavement above it to move together. The pavement itself is locally strained at the end of the transition slab (Fig. 1). By increasing the depth at the end of a moving transition slab, the displacements are better distributed, which can potentially allow for larger displacements and thus longer integral bridges.

For test TST3, on the contrary, the crack appeared right at the slab head, even for just small displacement values. Mechanically, the soil and the pavement above the transition slab did not move when the transition slab was pulled, and remained connected to the soil and the pavement further away from the bridge end. Consequently, a crack opened right at the bridge end. This is unfavourable as ingress of saltwater and other aggressive products could occur at this sensitive location.

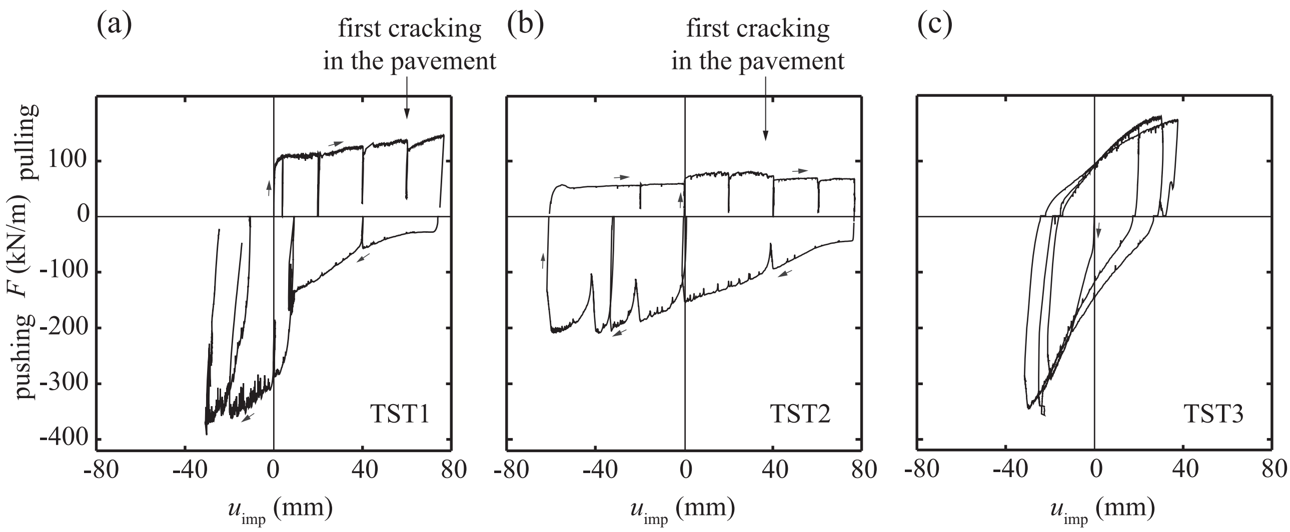

Fig. 7. Horizontal applied force F vs. imposed displacement u_{imp}; a) TST1, b) TST2, c) TST3

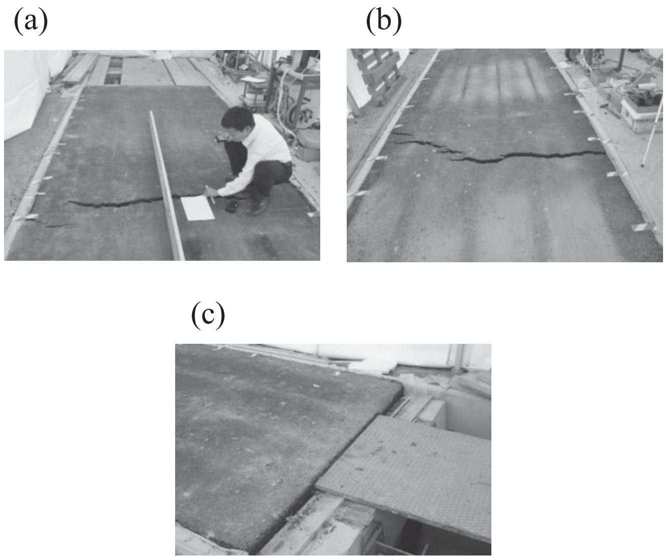

Fig. 8. Crack in pavement during pulling: a) above end of transition slab in TST1 (3.50 m < x_{crack} < 4.50 m), b) above end of transition slab in TST2 (3.50 m < x_{crack} < 4.50 m), c) at bridge end of transition slab in TST3 (x_{crack} = 0 m)

One important conclusion that can be drawn from the observation of surface cracks in the pavement is that the condition of the top surface of the transition slab is critical for limiting the crack opening in the pavement at the ends of integral bridges. To ensure that the soil above the transition slab moves with it, its top surface needs to be sufficiently rough.

6.3 Surface displacement of pavement and displacement of transition slab during pulling

Fig. 9 shows the measured surface displacements for all three tests for the first pulling phase. The results for TST3 are not entirely comparable, as a pushing phase had been performed previously. For all three tests, the longitudinal displacement profile closely corresponds to what has already been reported about cracking. For TST1 and TST2, the pavement moved almost as much as the displacement applied to the slab head for most of the length of the transition slab, and then a sharp transition occurred near the end of the transition slab, with small longitudinal displacements for x > 5 m (Figs. 9b and 9d). For TST3, the crack formed at x = 0 and almost no longitudinal displacement of the pavement was observed over the transition slab and further away.

Fig. 10 shows the longitudinal strains in the pavement before cracking for TST1 and TST2. A similar maximum level of strain was observed in both configurations, whereas the longitudinal displacement in the case of TST1 (40 mm) was twice that of TST2 (20 mm), which again shows the favourable effect of the larger buried depth at the end of the transition slab. Taking into consideration the fact that only two results are used, a tentative linear relationship between the peak longitudinal strain

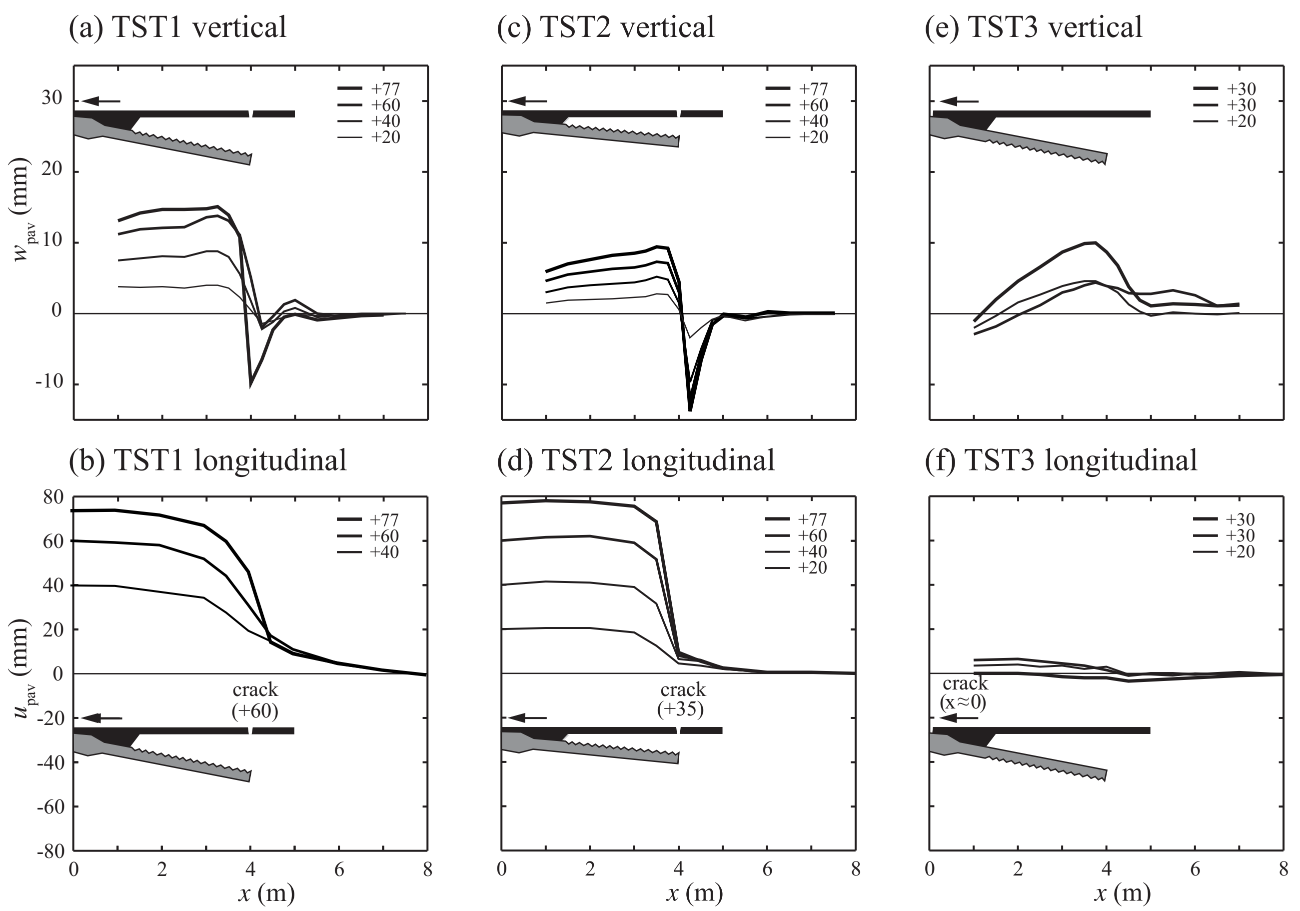

Fig. 9. Vertical and longitudinal displacements of pavement in pulling phase (bridge shortening) as a function of the distance from the bridge end; load steps refer to imposed displacement u_{imp} (mm)

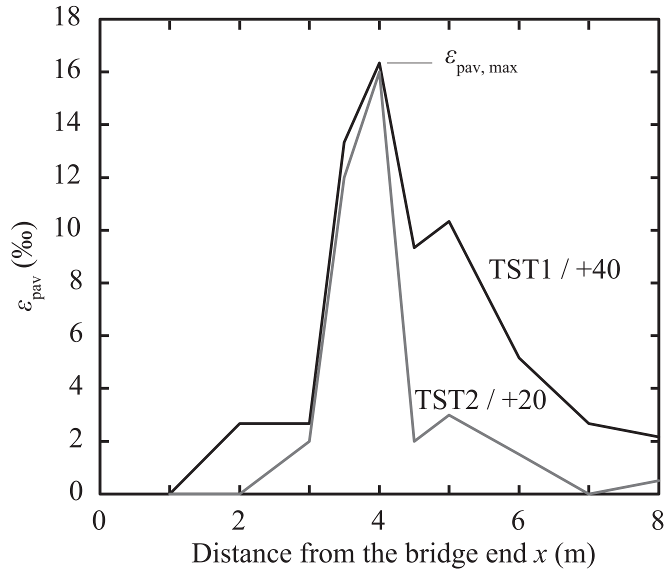

Fig. 10. Pavement strain profile ε_{pav} before cracking as a function of the distance from the bridge end; TST1 with $u_{imp} = +40$ mm and TST2 with $u_{imp} = +20$ mm

$\varepsilon_{pav,max}$ and the imposed longitudinal displacement u_{imp} can be derived as shown in Eq. (1):

$$\varepsilon_{pav,\max} \approx \frac{0.3 \cdot u_{imp}}{h} \tag{1}$$

where h is the buried depth at the end of the transition slab.

This expression needs to be confirmed by further experimental investigations.

The measured maximum strain has to be compared with the maximum allowable strain in the pavement, which depends on pavement type, temperature and strain rate. Regarding vertical displacements, Figs. 9a and 9c show that for TST1 and TST2, the vertical restraint provided by the steel columns was not completely activated because of some play in the connections, allowing fairly large upward vertical displacements at the slab head. The fact that the various profiles are nearly horizontal over the length of the transition slab and that the vertical displacement at the slab head is proportional to the applied displacement multiplied by the inclination indicates that it slid over its smooth bottom surface. In TST2, owing to the removal of some of the soil (1:3 slope in Fig. 5), which was not the case in TST1, some rotation of the slab occurred in that area. For TST3, the behaviour was different, with a rough bottom surface that resulted in a strong rotation with some bending of the transition slab over its entire length.

6.4 Surface displacement of pavement and displacement of transition slab during pushing

Fig. 11 shows the surface displacements for all three tests for the first pushing phase. For TST1 and TST2, this phase

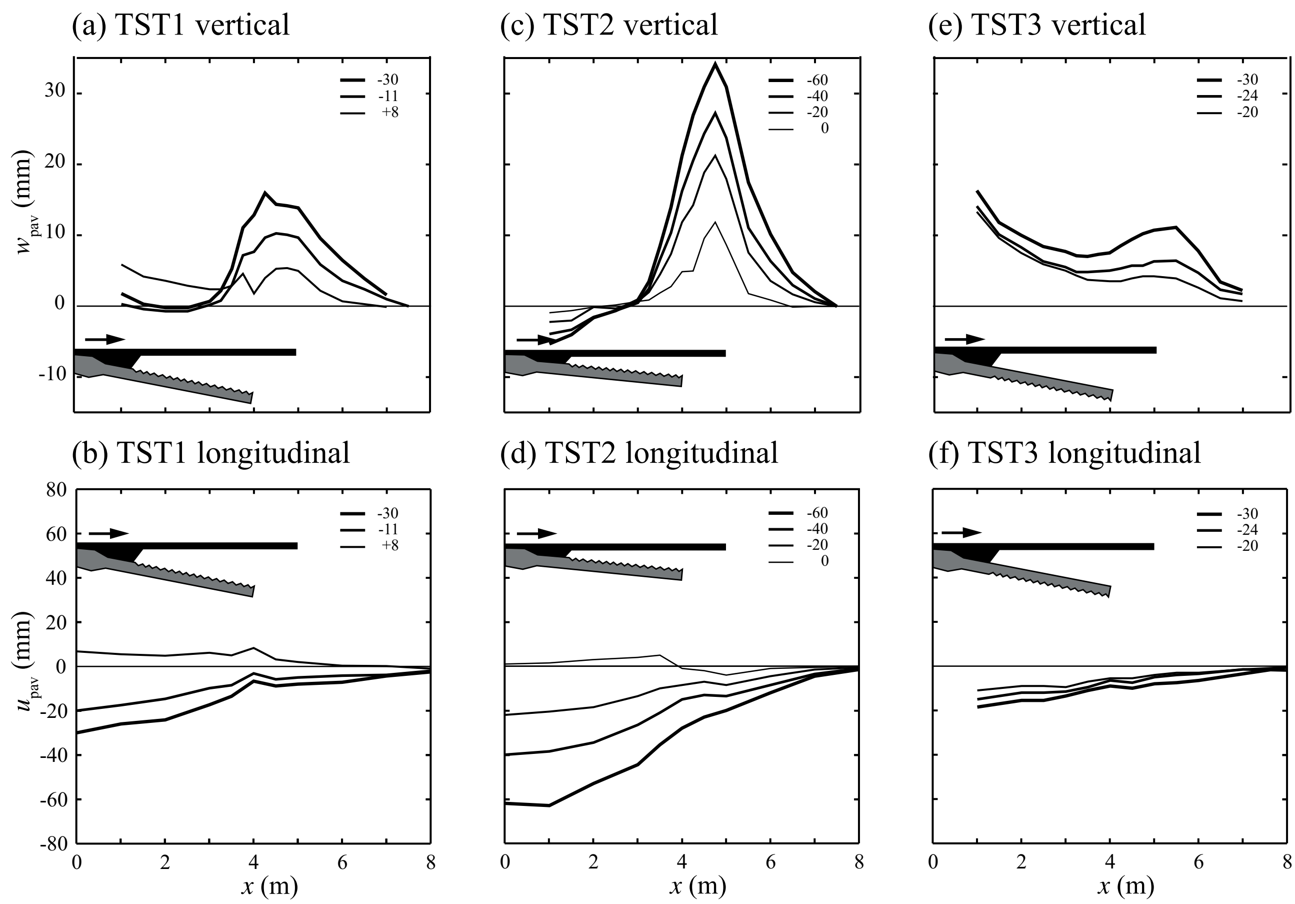

Fig. 11. Vertical and longitudinal displacements of pavement in pushing phase (bridge expanding) as a function of the distance from the bridge end; load steps refer to imposed displacement u_{imp} (mm)

was preceded by a pulling phase, whereas for TST3 it was its first displacement. The influence of the roughness of the top and bottom surfaces is quite visible. For TST1 and TST2, the smooth bottom surface of the slab allowed it to slide and move together with the top soil and pavement, with the result that a large bump was formed starting near the end of the transition slab and extending beyond it (Figs. 11a and 11c). For TST3, the slab's rough bottom surface prevented it from sliding and caused an uplift near its head and upward bending (Fig. 11e), along with a smaller bump at the end of the transition slab. Although the amplitude of the forces observed is similar to that of TST1 (Fig. 7), the deflected shape is quite different.

In the longitudinal direction, the pavement displacements propagated further away from the slab head than for displacements in the pulling phase.

7 Connection between bridge and transition slab

Fig. 12 shows possible bridge-transition slab connection details. As has been shown, large forces need to be mobilized to force the transition slab to move. The detail in Fig. 12a [5] cannot transfer large longitudinal forces unless a large number of high-capacity dowels are used. Employing this detail, the transition slab will usually not move (Fig. 2b). The detail in Fig. 12b has continuous top reinforcement between the bridge and the transition slab. Provided this reinforcement is properly designed and anchored, this solution can transfer a large force and cause the transition slab to move. This is why the latest edition of ref. [5] favours this detail. Nevertheless, a crack might form above the location of the partial joint. The solution shown in Fig. 12c, which provides a monolithic connection between the bridge and the transition slab, can transfer large forces and cause the transition slab to move with the bridge. The shaded area at the beginning of the transition slab needs to be carefully designed, as a plastic hinge can develop due to differential settlement. In this case its rotation capacity can be reduced by the presence of a combination of high moments, shear and tension [26].

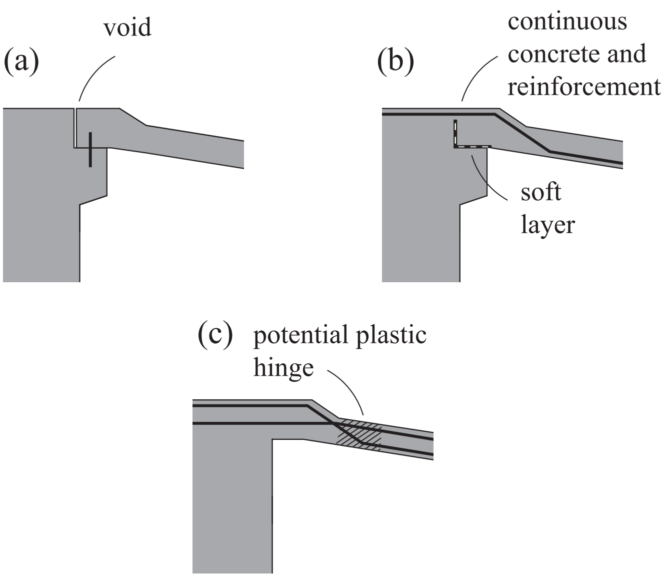

Fig. 12. Possible bridge-transition slab connection details: a) corbel and simple dowels, b) corbel and continuous top reinforcement, c) monolithic connection

8 Conclusions

The number of tests performed in this work is small, which does not allow definitive conclusions to be drawn. Nonetheless, some important observations were made:

- If the transition slab does not move together with the bridge, a crack will form at or near the bridge end, which is unfavourable (Figs. 2b and 8c). To enable the transition slab to move (Fig. 1), a longitudinally monolithic connection detail as shown in, for example, Figs. 12b and 12c, is required.
- The top surface of a moving transition slab needs to be sufficiently rough to avoid sliding of the soil above. Otherwise, it is likely that, in the case of bridge shortening, a crack will form at the bridge end of the transition slab (Fig. 4a). If the top surface of the transition slab is sufficiently rough, cracking of the pavement due to bridge shortening will be located approximately over the far end of the transition slab. This is less unfavourable as it is further away from the bridge (Figs. 4b, 8a and 8b).
- For moving buried transition slabs, the measured longitudinal strain in the pavement before cracking appears to be inversely proportional to the buried depth at the end of the transition slab. An increase in the buried depth decreases the strains in the pavement and, consequently, the risk of cracking. This can be achieved by either increasing the length of the transition slab or its inclination, or by a combination of both. Starting the transition slab at a lower point on the bridge side is also a possibility.
- The surface of the pavement undergoes some vertical displacements due to the longitudinal movements of the bridge end. The resulting bumps and pits may have a negative effect on the comfort of bridge users (Figs. 3, 9 and 11).

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Notation

F	force applied to move transition slab
h	buried depth at end of transition slab
u	longitudinal displacement, movement at slab head
u_{imp}	longitudinal displacement imposed by bridge movement at slab head
u_{pav}	longitudinal displacement of pavement
w_{pav}	vertical displacement of pavement
x	distance from bridge end, distance from slab head
x_{crack}	distance between slab head and location of crack in pavement
ε_{pav}	longitudinal strain in pavement
$\varepsilon_{pav,max}$	maximum longitudinal strain in pavement at cracking
φ_k	internal angle of friction of backfill material

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