Influence of soil properties on the behavior of concrete pavements casted on dome-shaped interface elements

A. Comisini
Pontarolo Engineering, Cordovado, Pordenone, Italy

S. Secchi
CNR-ISIB, Padova, Italy

P. Simonini
Department IMAGE, University of Padova, Italy

Keywords: soil-structure interaction, subgrade properties, slabs, interface elements

ABSTRACT: Plastic dome-shaped interface elements posed between ground and concrete slabs may be an interesting method to realize industrial pavements, thus avoiding the use of classical and customarily utilized granular interface layer. To evaluate the effectiveness of this construction technique, a full-scale experimental investigation has been recently carried out. Its results have been used to calibrate a finite element model to describe the overall slab behaviour as a function of relevant geometrical and soil parameters. The paper outlines some interesting outcome of the tests carried out so far, showing also the applicability of the numerical model to suitably describe this soil-structure interaction problem.

1 Introduction

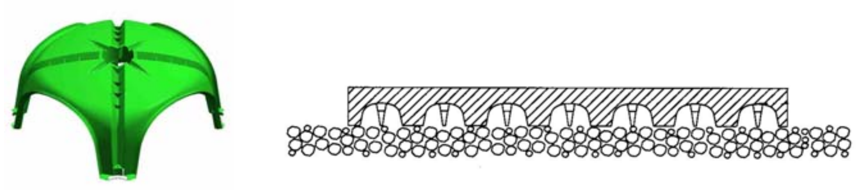
Plastic dome-shaped elements (PDSE) interposed between ground and concrete slabs may be an interesting alternative method to realize industrial pavements, avoiding therefore the use of the classical and customarily utilized granular layer between natural soil and concrete slab.

The typical PDSE is shown in Figure 1a. Each PDSE is interlinked with other PDSEs to create a formwork for successive complete casting of the concrete slab (Figure 1b). An additional advantage of PDSE system is to provide an internal orthogonal duct mesh allowing for free air-circulation, thus reducing possible humidity rise through the pavement.

To evaluate the effectiveness of this technique as a function of different PDSE types and subgrade conditions, an experimental research has been recently undertaken and partially carried out. To this end, a new reinforced-concrete test tank, in which typical subgrades supporting the dome-shaped concrete slabs, has been recently constructed. On these subgrades, several tests have been performed out by using different combinations of PDSEs and slabs, forcing them to failure by increasing vertical load and monitoring, along with the load increase, the vertical displacements for a careful reconstruction of the system deformed geometry.

The results of the experimental tests have been back-analyzed using the finite element method, in order to calibrate and validate a finite element model to describe the overall behaviour of the slabs as a function of soil conditions, type of dome-shaped plastic element and thickness/reinforcement of concrete slabs.

The paper outlines the most interesting results of some experimental tests carried out so far, as far as the effectiveness of the numerical analysis, that incorporates linear and non-linear models for subgrade response, to reproduce the interaction between ground and the pavement structure.



(a) (b)

Figure 1. Typical dome-shaped interface element (a) and final lay-out of the dome-shaped slab (b).

2 Experimental programme

In order to carry out the experimental programme, the reinforced-concrete test tank shown in figure 2a has been designed and constructed.

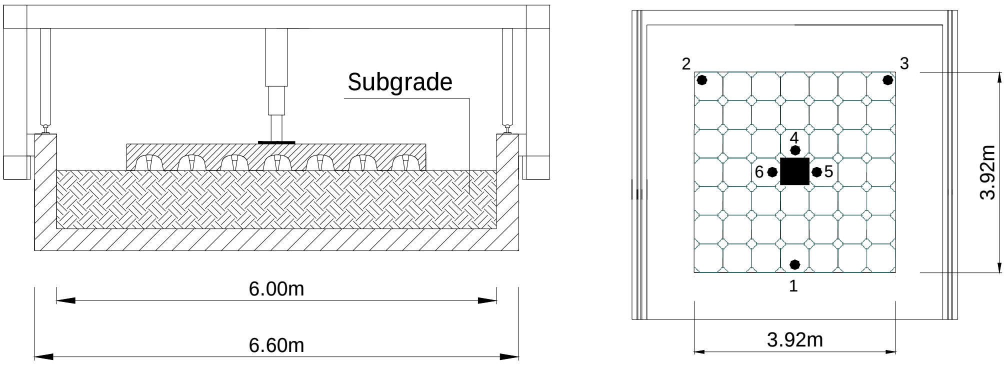
The dimensions in plan of the test tank are 6 m x 6 m with; the tank depth was selected to allow the preparation of foundation beds up to a maximum thickness of 1.5 m. The tank dimensions ensure that, during the stress-failure tests, the soil would be not affected by the restraints provided by the containment walls and by the concrete floor at the bottom.

The loading device comprises an arch with an hydraulic jack, that transmits the load to the dome-shaped slab through a square rigid steel plate with dimensions 56 x 56 cm. The loading system is provided with a load cell whilst six displacement transducers monitored the vertical displacements of the slab throughout all the tests. A view of the location of the vertical displacements transducers is provided in Figure 2b.

2.1 Subgrade preparation

Two different subgrades have been selected, to reproduce various ground stiffness conditions, namely:

i) An unique homogeneous layer of medium-fine silty sand (S1), with D_{50}=0.052 mm and U = 10 was used to reproduce a typical natural ground condition. This layer was compacted by moist tamping at 10% water content to reach a final dry unit weight = 15.7 kN/m^3.



(a) (b)

Figure 2. Lay-out of the testing system (a) and location of the six displacement transducers (b).

ii) A double layer system (S2), composed of a gravel layer with thickness = 30 cm compacted above the medium-fine silty sand S1. This second subgrade condition, used to evaluate possible improvement effect provided by the gravel onto the natural ground, was prepared by dynamically compacting a sandy gravel characterized by D_{50}=2.8 mm and U =20. The average final dry unit weight of the sandy gravel after compaction was γ_d= 20.4 kN/m^3.

Non-repetitive static plate load tests (ASTM D1196-93 - plate diameter = 30 cm) were carried out to characterize the stiffness of each subgrade. In addition some special plate tests were performed by using a 12 cm x 12 cm steel plate to reproduce as closely as possible the behaviour the feet of PDSEs, when posed onto the ground.

Figure 3 shows the plate vertical stress-settlement response measured on subgrade S1 and S2. Note the effect of plate size: as clearly expected, the plate with a size close to the PDSE breadth shows a much stiffer response when subjected to the same load increase. The presence of a poor concrete layer S3 above S1 increases at very high level the subgrade stiffness.

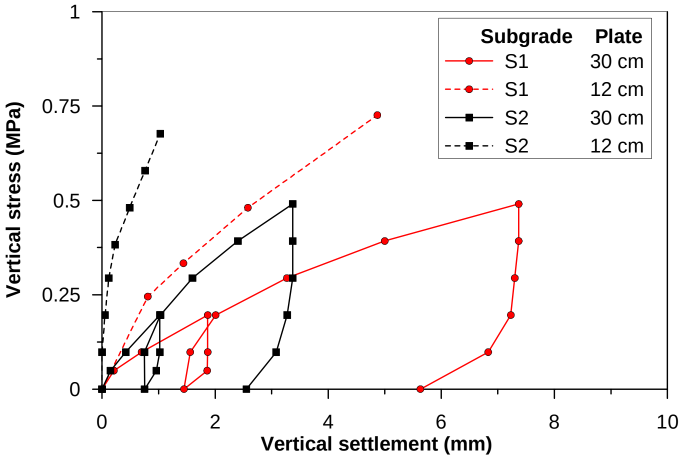


Figure 3. Load-displacement response from plate test carried out on different subgrades.

To interpret the stress-displacement response the classical Winkler elastic coefficient *k* was used. The interpretation of the vertical stress – settlement curve was performed by using a hyperbolic relationship (e.g. Duncan and Chang, 1970) evaluating the initial tangent stiffness, whose values are reported in Table 1. The hyperbolic curve was also used to model the non-linear stress-strain response in the finite element analysis.

Table 1. Values of stiffness coefficient from plate tests.

Plate [cm]	k_{S1} [N/cm^3]	k_{S2} [N/cm^3]
30	80	200
12	260	940

2.2 Test programme

23 loading tests formed the preliminary test programme considering various combinations of different type of PDSE, slab thickness and reinforcement, formed by welded nets, were considered.

A typical test configuration includes 7×7 modules installed side-by-side and covered by in-situ casted concrete. The load was then applied via the hydraulic jack up to the breakage of concrete slab, due to the typical mechanism of shear-bending rupture. As a matter of fact, the most significant load distribution, during the pavement life under service condition, is that maximizing the bending moments, the break generally occurring by exceeding the flexural strength. The test was devised so that, after an initial loss of stiffness due to the initial flexural rupture, the load may be increased again, up to the triggering of a punching failure mechanism.

An additional test (N. 24) was carried out by casting a traditional concrete slab on to the gravelly layer S2, without interposing the PDSEs. This test was performed in order to compare the PDSE solution on a typical ground with the classical and customarily used three layer system, composed by natural soil / gravel layer / slab.

The readings of vertical displacement were performed by the 6 transducers, whose arrangement was shown in figure 2b. Transducers 1,2,3, and 4 are in contact with the concrete slab measuring total vertical displacements DZ1, DZ2, DZ3 and DZ4, whereas transducers 5 and 6 measure the relative displacements DZ5 and DZ6, as depicted in Figure 4.

The pictures of Figures 5a,b show a typical view of the PDSE pavement before load application and at the end of the test, characterized by a clear punching failure of the PDSE slab.

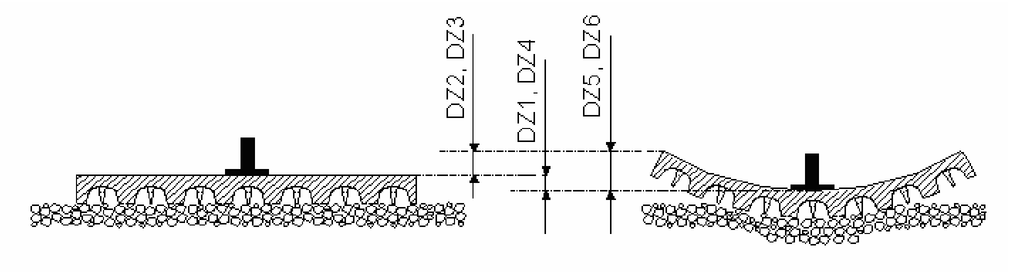


Figure 4. Relevant vertical displacements of the pavement under load increase.

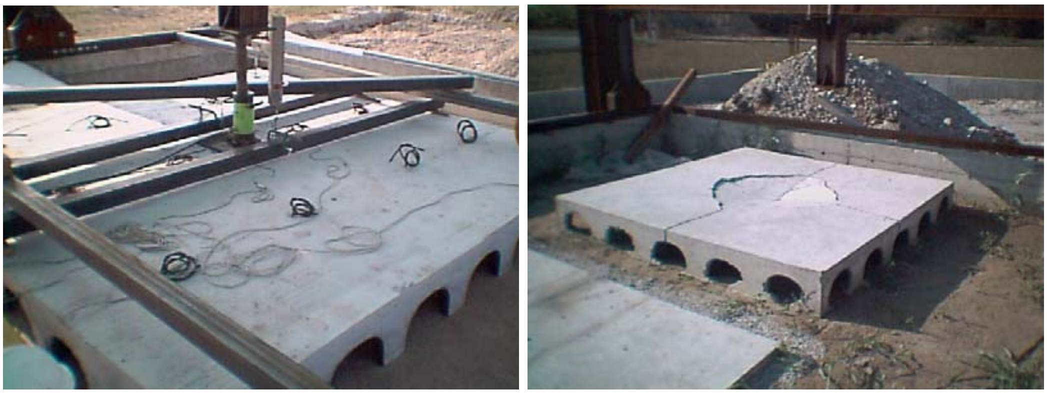


Figure 5. General view of the test tank with a) a typical pavement on PDSEs before load application and b) at the end of the test.

Among the various tests carried out so far, only a few of them are described here and modeled by the finite element method, to show mostly the effect of different ground stiffness on the overall response.

3 Numerical modelling and comparison with experimental data

To model the overall behaviour of the pavement both 2D and 3D FE Model were used (e.g. Bathe, K.J., 1996).

3-D option seemed however an almost obvious choice, in order to correctly represent the complex geometry of the pavement and the inelastic mechanical behaviour of the slab. In addition, 3D analysis was preliminarily used to evaluate the effectiveness of a simpler equivalent 2D approach, to be friendly used for the design of PDSE slabs in common engineering practice.

To limit the number of degrees of freedom - by considering the various symmetries and imposing restraints by using Lagrange multipliers - only one eighth of the structure was schematised as depicted in figure 6. The mesh is formed by approximately 33,000 nodes and 150,000 4-node isoparametric bricks. The corresponding degrees of freedom are approximately 100,000.

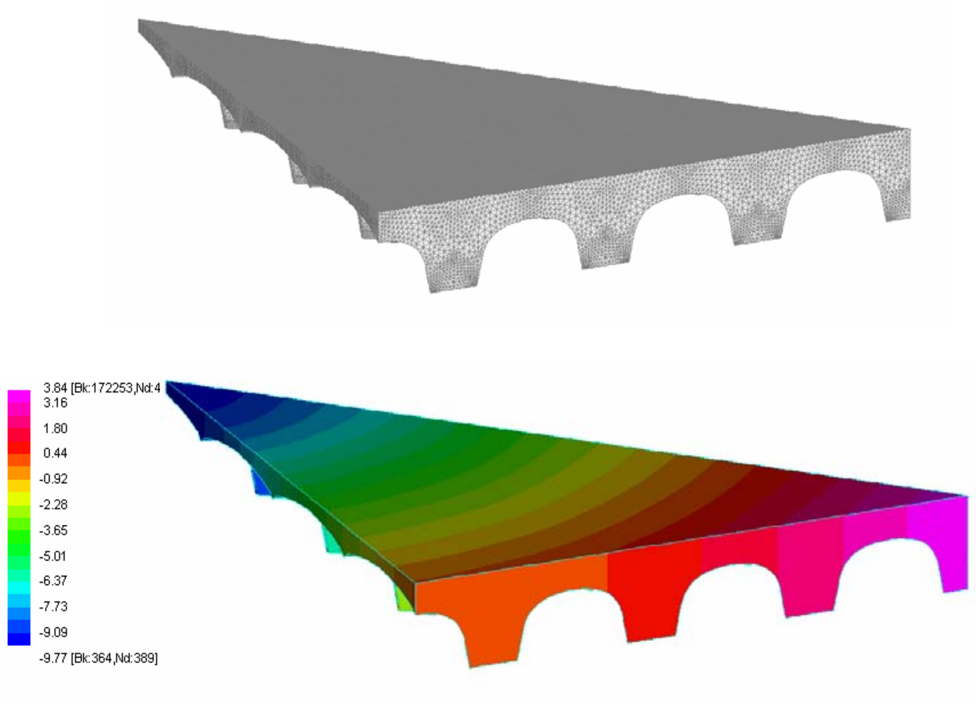


Figure 6. Finite element mesh for 3D analysis (top, 1/8 of the whole domain) and corresponding contour map of vertical displacements (bottom).

The constitutive model used to describe concrete response is the Mohr-Coulomb (e.g. D. R. J. Owen, E. Hinton, 1980) criterion (ϕ=65° and c=2.0 MPa), whereas the soil response was modelled using linear and non-linear elastic springs, whose calibration was performed on the basis of plate test results (Table 1 -) and back-analysis of full scale tests.

Figure 7 (left) depicts the trends of the vertical displacement for the typical case of PDSE slab resting on subgrade S1 (height = 260 mm plus 50 mm of casted concrete). Both elastic and elastoplastic analyses ware performed and referred as fem_23a and fem_23b respectively.

The overall behaviour of the PDSE slab has been compared with that provided by the classical solution formed by the concrete full slab, charaterized by and equvalent thickness of 75 mm, casted necessarily on the gravel subgrade (figure 7 right).

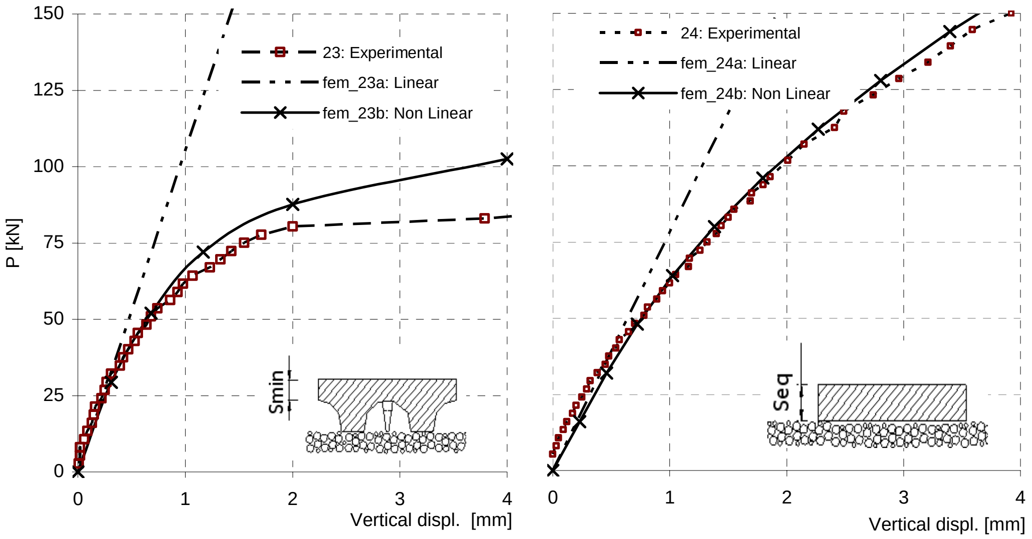


Figure 7. Load vs. vertical displacement DZ4: PDSE (left) full slab 7.5 cm thick (right)

Featues to note are:

- The initial response of PDSE slab is somewaht stiffer than the one given by the full slab, almost up to P_{min}=30 kN, which may represents a possible upper bound for the limit condition;
- A fully plastic behaviour is observed for PDSE slab above P=80 kN, whereas the complete final rupture by punching occurs at P= 160 kN for the classical full slab solution;
- Beyond P_{min}= 30 kN, the concrete plasticitazion begins to occur: this load, divided by a concrete safety factor, may therefore represent an upper load in service condition.
- The finite element analyses carried out with the non linear material models seem to describe properly the experimental results for both PDSE and classical slab;

Below P_{min}=30 kN, the overall behaviour of the classical full slab on the gravel layer can be considered totally equivalent to the PDSE slab, which can be therefore easily modelled with 2D shell elements interacting with the soil characterzed by non linear springs.

Comparing the results obtained from 3D analyses with the equivalent 2D approach it is possibile to propose the following equivalence between the minimum thickness s_{min} of the concrete slab casted above PDSE elements and the thickness of the classical full slab s_{eq}.

$$s_{eq} = f(k,s_{min})\cdot s_{min} \qquad (1)$$

The homogeneization ratio f depens on the shape of the plastic dome element, on the soil stiffness and on the minimum thickness s_{min} of the above casted concrete. Function (1) provides values always above the unity, whereas the limit $f=1$ is reached by increasing significantly s_{min}.

The major advantages of using PDSEs, due to their particular dome shape, are obtained with thickness s_{min} in the range 40÷80 mm, beyond which the dome effect decreases significantly towards a mechanical behaviour typical of the full slab with $s=s_{min}$.

The stiffness equivalence holds only within the concrete linear response, that is for $P<P_{min}$ and the results of the above analyisis may be applied to other cases only if the above hypotesis is satisfied.

Figure 8 illustrates the trend of f as a function of s_{min} for both subgrades S1 and S2, in the case of stiffness k_{S1}= 80 N/cm^3 and k_{S2} =200 N/cm^3 (referred to the standard 30 cm diameter plate).

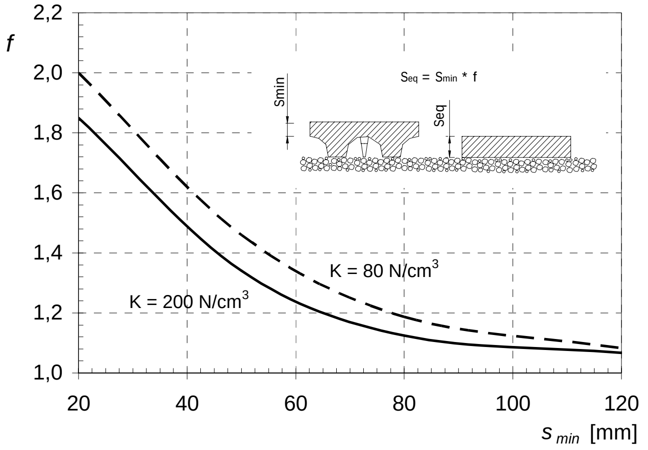


Figure 8. Equivalent thickness ratio vs. minimum thickness of the PDSE slab.

The influence of different soil condition has been considered by analyzing the results of two typical experimental tests and modelled with the finite element method. A typical case of a PDSE slab with total height equal to 340 mm (260 mm plastic dome shaped elements plus 80 mm casted undereiforced concrete) was studied using the 2D approach with an equivalent thickness s_{eq} = 80·*f* = 96 mm. Material models are linear elastic for concrete and non linear hyperbolic for both subgrade S1 and S2.
Figure 9 compares the results of experimental tests and numerical analyses. It is interesting to note that, up to loads P ≅ 75 kN, the numerical results fit rather well the experimental data even though only the soil non linearity is taken into account. In other words, the simplified 2D analysis with non linear hyperbolic subgrade, seems able to describe the overall DPSE slab response up to relatively large loads, exceeding serviceability condition.

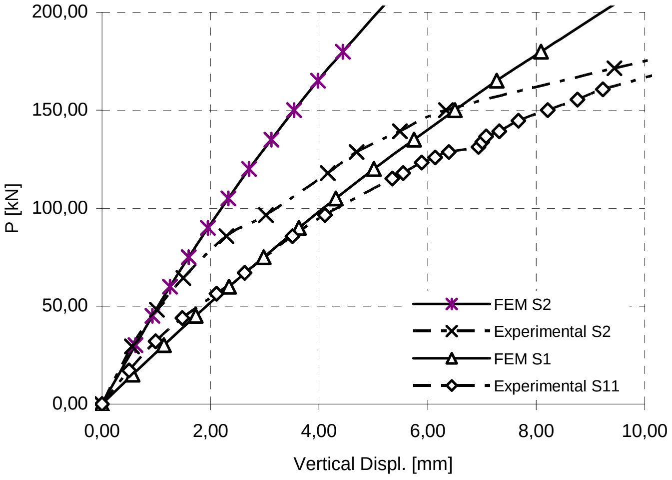


Figure 9. Comparison between experimental load tests and FE analysis.

The effect of soil type is clearly evident: the gravel layer provides a relatively stiffer response with respect to the natural silty sand. However, it is important to note that the maximum vertical displacement at the centre of the slab is in both cases very small and, within loads of P=40 kN, does exceeding 2 mm. The stiffness of the DPSE system reduces, in fact, the influence of subgrade type on the overall response, thus allowing for the direct installation of DPSEs on the compacted natural ground (no gravel layer interposition), when the subgrade condition are not excessively poor. In this latter situation, possible introduction of welded net may increase the slab stiffness as a compensation of reduction of subgrade properties.

4 Conclusions

The effectiveness of DPSE system as alternative technique to realize industrial pavement has been evaluated through a full scale experimental investigation. A finite element approach to describe the overall pavement behaviour has then been used to model the experimental results.

On the basis of the experimental research and numerical analysis carried out so far, the following main conclusions can be drawn:

- The model tests provided relevant information on the mechanical response of the PDSE slabs as function of soil conditions, type of dome-shaped plastic element and thickness/reinforcement;
- The soil response was measured through plate load tests, whose results have been interpreted and modelled using an hyperbolic load-displacement model, implemented in the finite element model;
- Within serviceability condition, the DPSE system showed a stiffness comparable to that provide by the classical full slab posed on a granular interface layer;
- The PDSE slab behaviour is characterized by a punching failure mechanism of the concrete slab whereas classical full slab shows a continuous hardening up to larger loads;
- 3D finite element elasto-plastic finite element analysis, calibrated on the results of experimental test resultys, was capable to properly model the soil-dome shaped slab interaction, even approaching the failure condition;
- On the basis experimental test results and of the 3D finite element analysis, a simpler and quicker 2D finite element approach has been evaluated, by introducing an equivalent thickness to reproduce the response of the complex dome shaped slab;
- Within loads in serviceability condition, the simple 2D analysis coupled with non linear springs seems to be able to describe the PDSE slab behaviour and can be proposed as simple and economical method for the design of this type of pavement.

Finally, the effect of subgrade stiffness seemed to play not a relevant role in serviceability condition for this type of pavement, that is, if natural subgrade not excessively poor, the PDSE elements can be posed directly on to the compacted natural soil, thus saving the interposition of the granular layer.

5 References

ASTM, 1993. Nonrepetitive Static Plate Load Tests of Soil Flexible Pavement Components (D1196-93)

Duncan, J.M. and Chang, C.Y. (1970). Non-linear analysis of stress and strain in soils. ASCE, J. Geot. Eng. Div., SM5, pp. 1629-1653.

Bathe, K.J. (1996). Finite element procedures / Klaus-Jurgen, Englewood Cliffs, Prentice Hall

D. R. J. Owen, E. Hinton, (1980). Finite elements in plasticity : theory and practice