REPORT ON:

A
DESIGN SYSTEM
FOR
PAVEMENTS
SURFACED WITH
PIETRA PAVERS

BY

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OCTOBER 2018

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CONTENTS

BRIEF

Discussions between Alan Lovell and John Knapton during 2018 have led to the development of the following brief.

Conventional Pietra Pave Structural Design Standard Project

Aim
To develop Pietra Pave Conventional Pavements Structural Design Methodology, using the properties of Pietra Pave jointing material.

To develop a new design standard for Pietra Pave pavements based upon mechanistic design principles.

Development of a new understanding of design
The information upon which the new approach will be based includes, but is not limited to:

Relevant part of BS7533, i.e.
BS 7533-10:2004
Pavements constructed with clay, natural stone or concrete pavers —
Part 10: Guide for the structural design of trafficked pavements constructed of natural stone setts

Other British Standard & Highways Agency design guidance

Developments in relation to materials

Technical data on the inclusion and impact of geogrids in the subbase and capping layers

Details
Based upon the Finite Element approach, produce a structural design methodology which will allow the user to produce Pietra Pave pavement section designs to satisfy commonly encountered applications. This design methodology will include the design loading of vehicle type supplemented by that of cumulative standard axles (CSA).

The work will also review the current capping layer recommendations;
- allowing for 1% CBR
- consideration of 5% rather than 6% as current "no capping layer required" as many Site Investigation reports' default is 5% CBR
- Capping layer depth at low CBR and light loading

The applications to be considered are:

1/ Non-trafficked footways
2/ Domestic scale driveways trafficked by cars

3/ Domestic scale driveways trafficked by light vans
4/ Commercial driveways and car parks trafficked by cars, light vans and delivery vans (up to 7.5t gvw)
5/ Pavements trafficked mainly by light vehicles but by occasional HGVs.
6/ External hard standings trafficked by highway vehicles (e.g. distribution warehouses)
7/ Pavements trafficked by HGVs whose volume can be measured in millions of standard axles

Deliverables
The deliverables will comprise:

A/ A Structural Design Methodology which includes charts and examples for the structural design of each of the above categories, including:-
Updated standards and references
Inclusion of new material properties (change in PEN for DBM etc)
Inclusion of geogrids and if considered appropriate confinement systems.

B/ A report setting out the basis of the design method. This will be largely for Banister Halls' internal consumption and training.

C/ Training for Banister Hall's staff.

INTRODUCTION

This Report provides revised design guidance for Pietra Pave surfaced pavements. The guidance is based upon many inputs as this report explains including, most importantly, the author's 40 years' experience of the successful use of small element pavements.

This report combines two design methodologies. For lightly trafficked pavements, the loads applied by wheels are the critical factor and the guidance for those pavements is based upon their weights. This is known as *ultimate load design*. For heavily trafficked highway pavements, the pavements are designed on the basis of the cumulative number of standard 8,000kg axles, in line with the UK Highways England design approach. This is known as *serviceability design*.

Because the starting point for this Report was BS7533: Part 10, I have included as Appendix A the relevant extracts from that standard which provide guidance for the categories of pavements to which this Report applies. Also, I have included tables illustrating the BS7533: Part 10 design sections alongside my proposed design sections for convenient comparison.

PIETRA PAVE JOINTING MATERIAL TEST RESULTS

AECOM

SUMMARY OF INDIRECT TENSILE STIFFNESS MODULUS (ITSM) DATA

UKAS TESTING 4410

BS EN 12697-26 : 2004 (Annex C)

Project Title : **Bannister Hall Nursery**		Tested By : **WG**
Job Number : **8219858**	Location of Testing : **AECOM Laboratory, NG9 6RZ**	Reported By : **WG**
Ticket Number : **T1294**	Date of Issue : **01 October 2018**	Checked By : **NAL**

Sample Reference	Thickness (mm)	Diameter (mm)	Bulk Density (kg/m³)	Horizontal Deformation at 20°C (microns)	Rise Time at 20°C (m.sec)	**ITSM at 20°C (MPa)**
1	59.1	100.8	2426	5.0	124	**11760**
2	59.6	100.8	2394	5.0	124	**11730**
3	59.3	100.8	2430	4.9	124	**12330**
4	59.6	99.9	2423	5.0	124	**10870**
5	59.8	100.6	2466	5.0	124	**11320**
Test Annulus	70	150	n/a	n/a	n/a	Test Annulus Reference : 1-075 Test Annulus Percentage Difference : 1.5%

Comments and Deviations:

Origin of specimen : Laboratory Manufactured   Density Method Used : Procedure A - Dry

Checked by: -   Date: - **01 October 2018**

Created: 15/10/2015 EKD
Version: v2 24/02/2017
Printed on 01/10/2018

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0169 - FORM
Combined Testing
Lab Info\Controlled forms\Forms

AECOM

SUMMARY OF COMPRESSIVE STRENGTH DATA

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Bulk Reference :	**T1294**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Sample Reference	Date of Density / Test	Diameter : Prepared Length	Bulk Density (kg/m³)	**Compressive Strength (N/mm²)**	Estimated In-Situ Cube Strength * (N/mm²)
1	25-09-18 / 27-09-18	1:0.98	2230	**12.9**	13.0
2	25-09-18 / 27-09-18	1:0.98	2300	**12.0**	12.0
3	25-09-18 / 27-09-18	1:0.99	2380	**12.6**	12.5
4	25-09-18 / 27-09-18	1:0.98	2400	**11.7**	11.5
5	25-09-18 / 27-09-18	1:0.99	2400	**13.2**	13.0

Comments and Deviations:

* National Annex NA (informative) Guidance on the use of BS EN 12504-1

Checked by: - NA [signature] Date: - **01 October 2018**

AECOM

COMPRESSIVE STRENGTH AND DENSITY OF CORE SPECIMENS

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Core Number:	**1**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Dimensions :

Average Length : 99.5 mm
Average Prepared Length : 99.5 mm
Average Diameter : 101.0 mm
Ratio of Diameter : Prepared Length : 1:0.98

Examination Details :

Abnormalities Noted After Visual Examination : n/a

Aggregate Size : 2 mm
Aggregate Type : Other

Reinforcement Details :

	As Received		After Capping	
	Distance from Top (mm)	Diameter (mm)	Distance from Top (mm)	Diameter (mm)
Bar 1	n/a	n/a	n/a	n/a
Bar 2	n/a	n/a	n/a	n/a
Bar 3	n/a	n/a	n/a	n/a
Bar 4	n/a	n/a	n/a	n/a

Test Results :

Sample Condition : Water Saturated
Test Temperature : 20.2ºC

Density : 2230 kg/m³
Maximum Load at Failure : 103.4 kN
Compressive Strength : 12.9 N/mm²
Appearance at Failure : Type J - Unsatisfactory, Normal
Estimated in-situ cube strength : 13.0 N/mm²

f_c = Compressive Strength (N/mm2)
F = Max Load at Failure (N)
A_c = Cross Sectional Area (P*dm2/4)

Comments and Deviations:

Date of Coring : n/a
Date of Test : 27 September 2018

Determination of volume by water displacement method.
For water saturated - specimens conditioned for a minimum of 48 hours prior to testing.
End preparation by sulphur mixture method to BS EN 12390-3 Annex A.4.
Calculation and result from National Annex NA Guidance on the use of BS EN 12504-1:2009

Checked by: - N A [signature] Date: - **01 October 2018**

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COMPRESSIVE STRENGTH AND DENSITY OF CORE SPECIMENS

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Core Number:	**2**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Dimensions :

Average Length : 99.2 mm
Average Prepared Length : 99.2 mm
Average Diameter : 101.5 mm
Ratio of Diameter : Prepared Length : 1:0.98

Examination Details :

Abnormalities Noted After Visual Examination : n/a

Aggregate Size : 2 mm
Aggregate Type : Other

Reinforcement Details :

	As Received		After Capping	
	Distance from Top (mm)	Diameter (mm)	Distance from Top (mm)	Diameter (mm)
Bar 1	n/a	n/a	n/a	n/a
Bar 2	n/a	n/a	n/a	n/a
Bar 3	n/a	n/a	n/a	n/a
Bar 4	n/a	n/a	n/a	n/a

Test Results :

Sample Condition : Water Saturated
Test Temperature : 20.2ºC

Density : 2300 kg/m³
Maximum Load at Failure : 97.3 kN
Compressive Strength : 12.0 N/mm²
Appearance at Failure : Type L - Unsatisfactory, Normal
Estimated in-situ cube strength : 12.0 N/mm²

f_c = Compressive Strength (N/mm2)
F = Max Load at Failure (N)
A_c = Cross Sectional Area (P*dm2/4)

Comments and Deviations:

Date of Coring : n/a
Date of Test : 27 September 2018

Determination of volume by water displacement method.
For water saturated - specimens conditioned for a minimum of 48 hours prior to testing.
End preparation by sulphur mixture method to BS EN 12390-3 Annex A.4.
Calculation and result from National Annex NA Guidance on the use of BS EN 12504-1:2009

Checked by: - N A [signature]

Date: - **01 October 2018**

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COMPRESSIVE STRENGTH AND DENSITY OF CORE SPECIMENS

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Core Number:	**4**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Dimensions :

Average Length : 99.0 mm
Average Prepared Length : 99.0 mm
Average Diameter : 101.0 mm
Ratio of Diameter : Prepared Length : 1:0.98

Examination Details :

Abnormalities Noted After Visual Examination : n/a

Aggregate Size : 4 mm
Aggregate Type : Other

Reinforcement Details :

	As Received		After Capping	
	Distance from Top (mm)	Diameter (mm)	Distance from Top (mm)	Diameter (mm)
Bar 1	n/a	n/a	n/a	n/a
Bar 2	n/a	n/a	n/a	n/a
Bar 3	n/a	n/a	n/a	n/a
Bar 4	n/a	n/a	n/a	n/a

Test Results :

Sample Condition : Water Saturated
Test Temperature : 20.2ºC

Density : 2400 kg/m³
Maximum Load at Failure : 93.7 kN
Compressive Strength : 11.7 N/mm²
Appearance at Failure : Type L - Unsatisfactory, Normal
Estimated in-situ cube strength : 11.5 N/mm²

f_c = Compressive Strength (N/mm2)
F = Max Load at Failure (N)
A_c = Cross Sectional Area (P*dm2/4)

Comments and Deviations:

Date of Coring : n/a
Date of Test : 27 September 2018

Determination of volume by water displacement method.
For water saturated - specimens conditioned for a minimum of 48 hours prior to testing.
End preparation by sulphur mixture method to BS EN 12390-3 Annex A.4.
Calculation and result from National Annex NA Guidance on the use of BS EN 12504-1:2009

Checked by: - N A [signature]

Date: - **01 October 2018**

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COMPRESSIVE STRENGTH AND DENSITY OF CORE SPECIMENS

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Core Number:	**4**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Dimensions :

Average Length : 99.0 mm
Average Prepared Length : 99.0 mm
Average Diameter : 101.0 mm
Ratio of Diameter : Prepared Length : 1:0.98

Examination Details :

Abnormalities Noted After Visual Examination : n/a

Aggregate Size : 4 mm
Aggregate Type : Other

Reinforcement Details :

	As Received		After Capping	
	Distance from Top (mm)	Diameter (mm)	Distance from Top (mm)	Diameter (mm)
Bar 1	n/a	n/a	n/a	n/a
Bar 2	n/a	n/a	n/a	n/a
Bar 3	n/a	n/a	n/a	n/a
Bar 4	n/a	n/a	n/a	n/a

Test Results :

Sample Condition : Water Saturated
Test Temperature : 20.2ºC

Density : 2400 kg/m³
Maximum Load at Failure : 93.7 kN
Compressive Strength : 11.7 N/mm²
Appearance at Failure : Type L - Unsatisfactory, Normal
Estimated in-situ cube strength : 11.5 N/mm²

f_c = Compressive Strength (N/mm2)
F = Max Load at Failure (N)
A_c = Cross Sectional Area (P*dm2/4)

Comments and Deviations:

Date of Coring : n/a
Date of Test : 27 September 2018

Determination of volume by water displacement method.
For water saturated - specimens conditioned for a minimum of 48 hours prior to testing.
End preparation by sulphur mixture method to BS EN 12390-3 Annex A.4.
Calculation and result from National Annex NA Guidance on the use of BS EN 12504-1:2009

Checked by: - N A [signature] Date: - **01 October 2018**

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COMPRESSIVE STRENGTH AND DENSITY OF CORE SPECIMENS

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410

Project Title :	**Bannister Hall Nursey**	Tested By :	**JR/WG**
Job Number :	**8219858**	Reported By :	**JR/WG**
Core Number:	**5**	Checked By :	**NAL**
Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Date of Issue :	**01 October 2018**

Dimensions :

Average Length : 99.7 mm
Average Prepared Length : 99.7 mm
Average Diameter : 100.5 mm
Ratio of Diameter : Prepared Length : 1:0.99

Examination Details :

Abnormalities Noted After Visual Examination : n/a

Aggregate Size : 5 mm
Aggregate Type : Other

Reinforcement Details :

	As Received		After Capping	
	Distance from Top (mm)	Diameter (mm)	Distance from Top (mm)	Diameter (mm)
Bar 1	n/a	n/a	n/a	n/a
Bar 2	n/a	n/a	n/a	n/a
Bar 3	n/a	n/a	n/a	n/a
Bar 4	n/a	n/a	n/a	n/a

Test Results :

Sample Condition : Water Saturated
Test Temperature : 20.2°C

Density : 2400 kg/m³
Maximum Load at Failure : 104.5 kN
Compressive Strength : 13.2 N/mm²
Appearance at Failure : Type J - Unsatisfactory, Normal
Estimated in-situ cube strength : 13.0 N/mm²

f_c = Compressive Strength (N/mm2)
F = Max Load at Failure (N)
A_c = Cross Sectional Area (P*dm2/4)

Comments and Deviations:

Date of Coring : n/a
Date of Test : 27 September 2018

Determination of volume by water displacement method.
For water saturated - specimens conditioned for a minimum of 48 hours prior to testing.
End preparation by sulphur mixture method to BS EN 12390-3 Annex A.4.
Calculation and result from National Annex NA Guidance on the use of BS EN 12504-1:2009

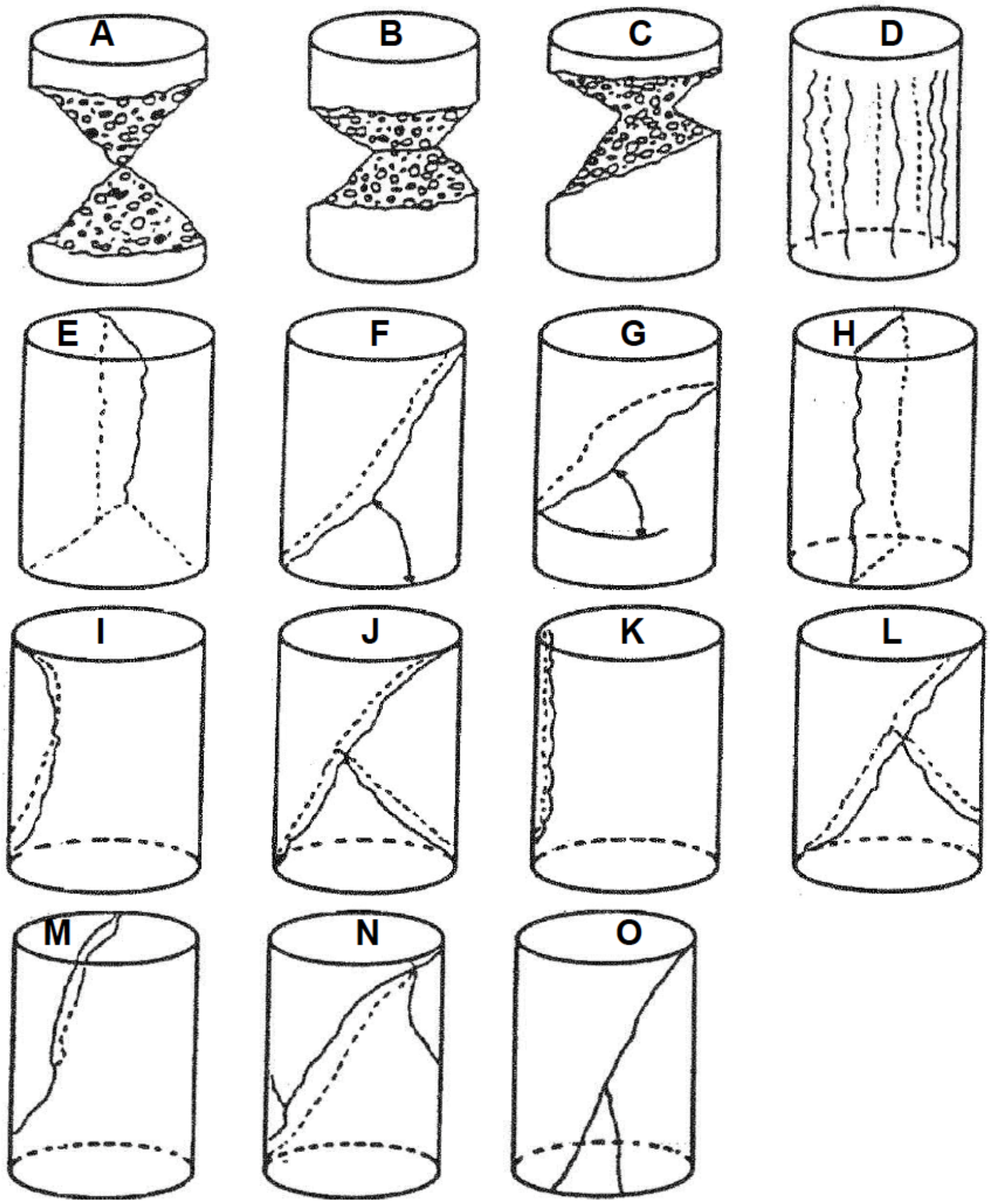
Checked by: - N A [signature]   Date: - **01 October 2018**

AECOM

COMPRESSIVE STRENGTH DATA FAILURE TYPES

BS EN 12504 - 1:2009 & BS EN 12390 - 1:2012, 3:2009 and 7:2012

UKAS TESTING 4410



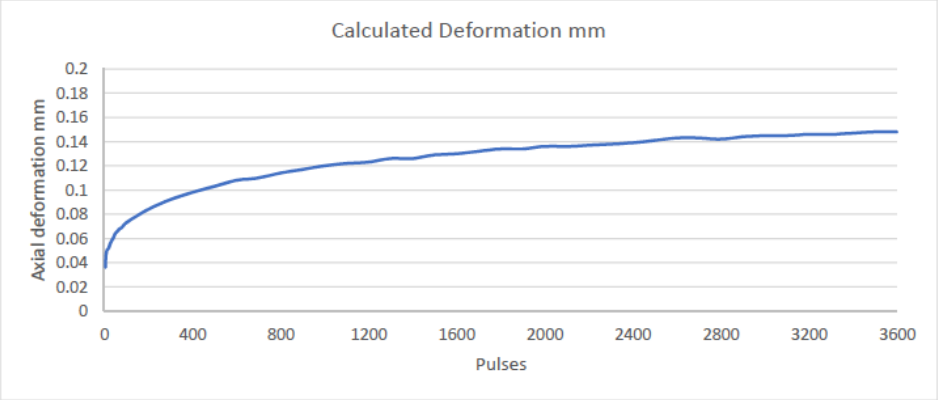
AECOM

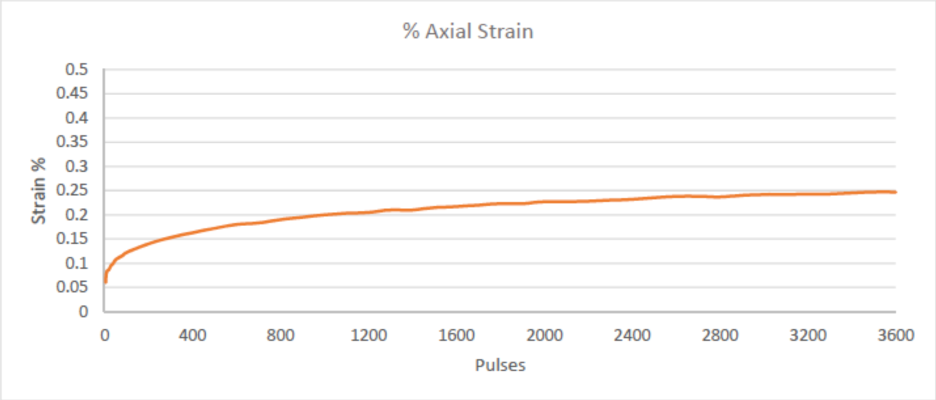
CYCLIC COMPRESSION TEST

BS EN 12697-25 - Test Method A1 - Cyclic Compression Test

Project Title :	**Bannister Hall Nursery**	Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Reported By :	**JR**
Job Number :	**8219858**	Date of Issue :	**01 October 2018**	Checked By :	**NAL**
Bulk Reference :	**T1294**	Tested By :	**JR**		

Test Sample:	**A**	**Test Conditions**		**Creep Characteristics**	
Sample Origin :	**Extracted from Site**	Test Temperature (°C) :	**45°C**	Permanent Deformation u_n (mm) :	**0.15**
Bulk Density (Mg/m³) :	**2.361**	Applied Stress (kPa) :	**100**	Cumulative Axial Strain ε_n (%) :	**0.25**
Density Method used :	**Procedure A - Dry**	Rest Stress (kPa);	**0.015**	Creep Rate f_c (μm) :	**0.10**
Diameter (mm) :	**149.7**	Maximum Cycles Applied :	**3600**	Creep Modulus E_n (Mpa) :	**39.3**
Thickness (mm) :	**60.4**	Applied Test Method / Pulse Loading Type :	**A1 / block**		





Comments and Deviations:

Checked by: - NA [signature]	Date: - **01 October 2018**

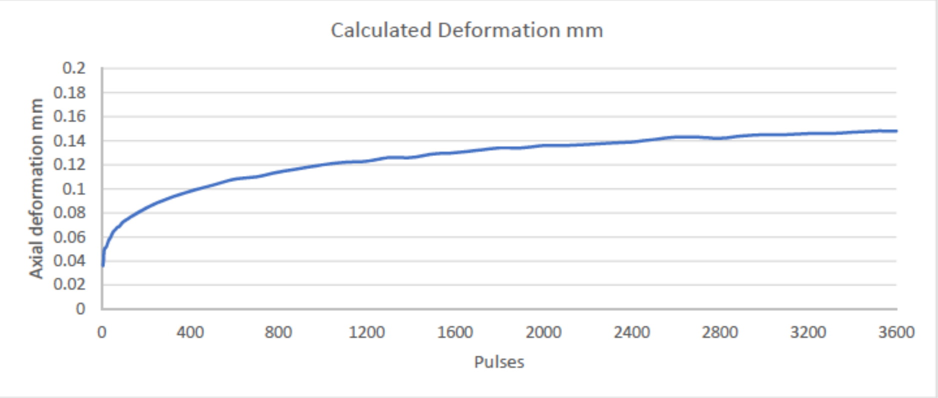
AECOM

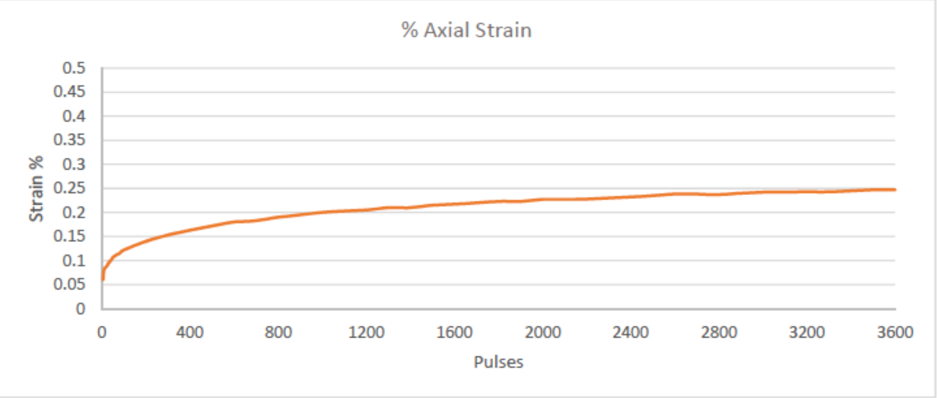
CYCLIC COMPRESSION TEST

BS EN 12697-25 - Test Method A1 - Cyclic Compression Test

Project Title :	**Bannister Hall Nursery**	Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Reported By :	**JR**
Job Number :	**8219858**	Date of Issue :	**01 October 2018**	Checked By :	**NAL**
Bulk Reference :	**T1294**	Tested By :	**JR**		

Test Sample:	**B**	**Test Conditions**		**Creep Characteristics**	
Sample Origin :	**Extracted from Site**	Test Temperature (°C) :	**45°C**	Permanent Deformation u_n (mm) :	**0.15**
Bulk Density (Mg/m³) :	**2.270**	Applied Stress (kPa) :	**100**	Cumulative Axial Strain ε_n (%) :	**0.25**
Density Method used :	**Procedure A - Dry**	Rest Stress (kPa);	**0.015**	Creep Rate f_c (µm) :	**0.09**
Diameter (mm) :	**149.6**	Maximum Cycles Applied :	**3600**	Creep Modulus E_n (Mpa) :	**40.2**
Thickness (mm) :	**61.4**	Applied Test Method / Pulse Loading Type :	**A1 / block**		





Comments and Deviations:

Checked by: -	N A [signature]	Date: -	**01 October 2018**

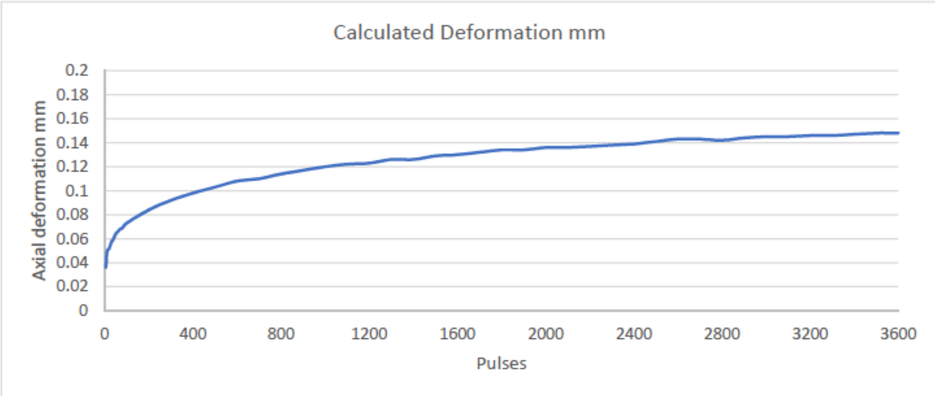
AECOM

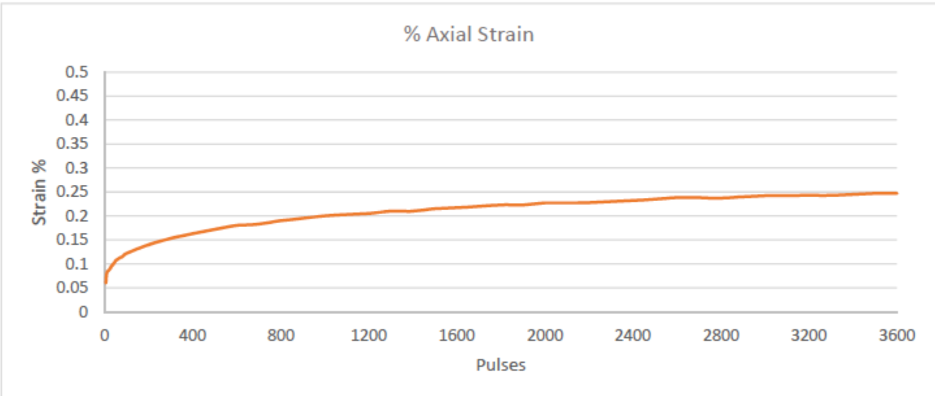
CYCLIC COMPRESSION TEST

BS EN 12697-25 - Test Method A1 - Cyclic Compression Test

Project Title :	**Bannister Hall Nursery**	Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Reported By :	**JR**
Job Number :	**8219858**	Date of Issue :	**01 October 2018**	Checked By :	**NAL**
Bulk Reference :	**T1294**	Tested By :	**JR**		

Test Sample:	C	**Test Conditions**		**Creep Characteristics**	
Sample Origin :	**Extracted from Site**	Test Temperature (°C) :	**45°C**	Permanent Deformation u_n (mm) :	**0.13**
Bulk Density (Mg/m³) :	**2.341**	Applied Stress (kPa) :	**100**	Cumulative Axial Strain ε_n (%) :	**0.22**
Density Method used :	**Procedure A - Dry**	Rest Stress (kPa);	**0.015**	Creep Rate f_c (µm) :	**0.04**
Diameter (mm) :	**149.3**	Maximum Cycles Applied :	**3600**	Creep Modulus E_n (Mpa) :	**46.2**
Thickness (mm) :	**59.7**	Applied Test Method / Pulse Loading Type :	**A1 / block**		





Comments and Deviations:

Checked by: - N A	Date: - **01 October 2018**

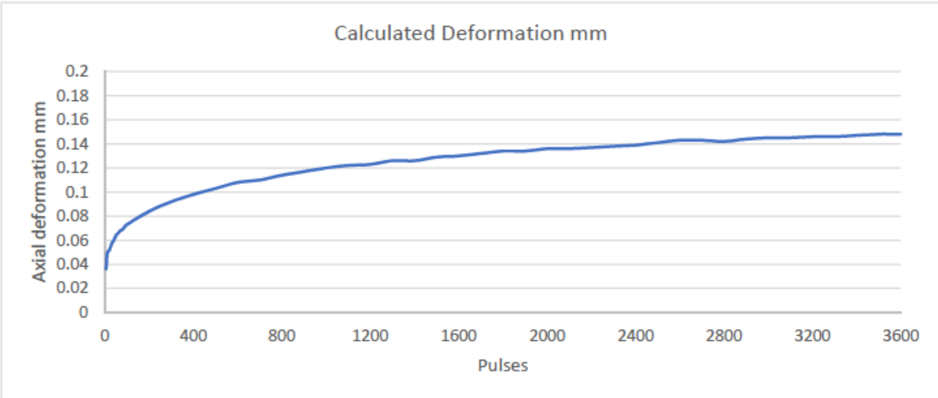
AECOM

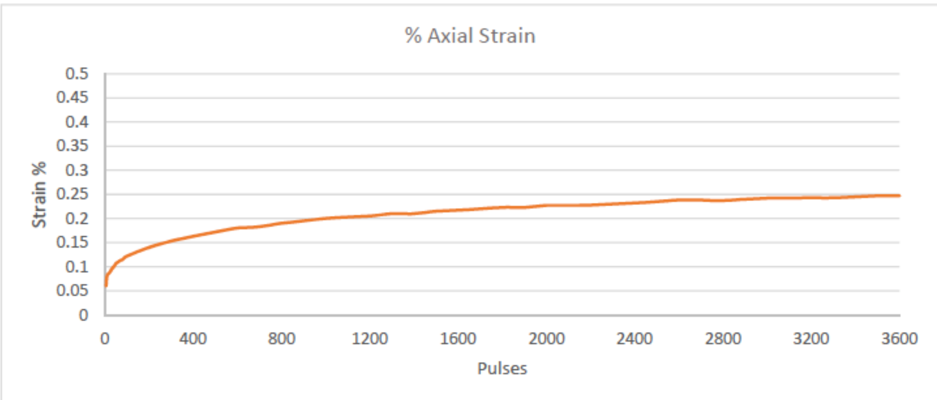
CYCLIC COMPRESSION TEST

BS EN 12697-25 - Test Method A1 - Cyclic Compression Test

Project Title :	**Bannister Hall Nursery**	Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Reported By :	**JR**
Job Number :	**8219858**	Date of Issue :	**01 October 2018**	Checked By :	**NAL**
Bulk Reference :	**T1294**	Tested By :	**JR**		

Test Sample:	**D**	**Test Conditions**		**Creep Characteristics**	
Sample Origin :	**Extracted from Site**	Test Temperature (°C) :	**45°C**	Permanent Deformation u_n (mm) :	**0.17**
Bulk Density (Mg/m³) :	**2.373**	Applied Stress (kPa) :	**100**	Cumulative Axial Strain ε_n (%) :	**0.27**
Density Method used :	**Procedure A - Dry**	Rest Stress (kPa);	**0.015**	Creep Rate f_c (μm) :	**0.07**
Diameter (mm) :	**149.1**	Maximum Cycles Applied :	**3600**	Creep Modulus E_n (Mpa) :	**36.7**
Thickness (mm) :	**60.5**	Applied Test Method / Pulse Loading Type :	**A1 / block**		





Comments and Deviations:

Checked by: -	N A [signature]	Date: -	**01 October 2018**

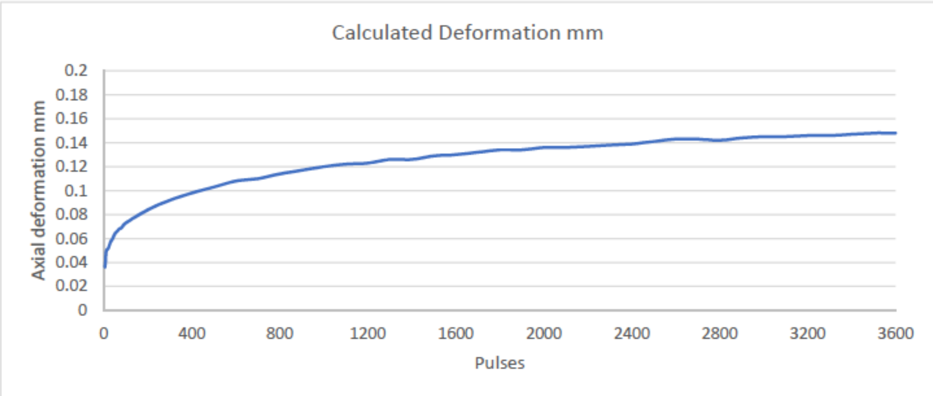
AECOM

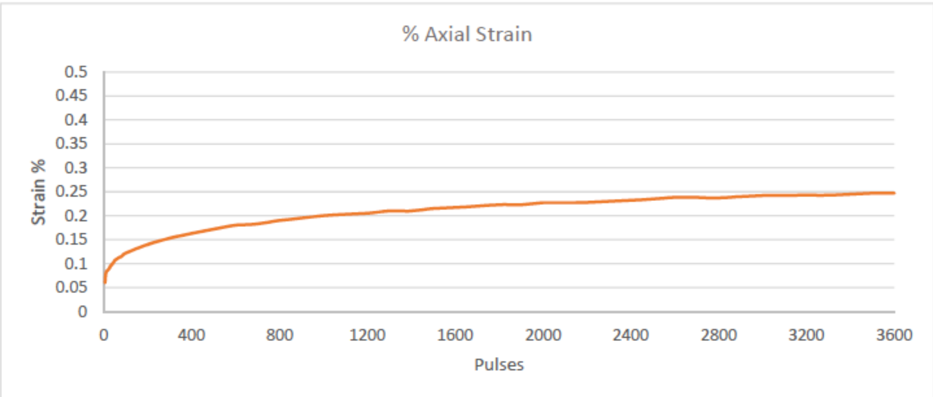
CYCLIC COMPRESSION TEST

BS EN 12697-25 - Test Method A1 - Cyclic Compression Test

Project Title :	**Bannister Hall Nursery**	Location of Testing :	**AECOM Laboratory, NG9 6RZ**	Reported By :	**JR**
Job Number :	**8219858**	Date of Issue :	**01 October 2018**	Checked By :	**NAL**
Bulk Reference :	**T1294**	Tested By :	**JR**		

Test Sample:	**E**	**Test Conditions**		**Creep Characteristics**	
Sample Origin :	**Extracted from Site**	Test Temperature (°C) :	**45°C**	Permanent Deformation u_n (mm) :	**0.11**
Bulk Density (Mg/m³) :	**2.338**	Applied Stress (kPa) :	**100**	Cumulative Axial Strain ε_n (%) :	**0.18**
Density Method used :	**Procedure A - Dry**	Rest Stress (kPa);	**0.015**	Creep Rate f_c (μm) :	**0.09**
Diameter (mm) :	**149.5**	Maximum Cycles Applied :	**3600**	Creep Modulus E_n (Mpa) :	**55.6**
Thickness (mm) :	**61.1**	Applied Test Method / Pulse Loading Type :	**A1 / block**		





Comments and Deviations:

Checked by: - NA

Date: - **01 October 2018**

DERIVATION OF PROPOSED PAVEMENT SECTIONS

I have derived the thicknesses and material types within the Tables which follow from a consideration of the design guidance provided in BS7533: Part 10 and the above test results. Much of the design guidance in BS7533: Part 10 has been derived from my own research into discrete element pavements starting in 1973. Therefore, the guidance in this document is informed by the author's 40 years experience in the field of designing pavements surfaced by discrete elements.

I have reviewed the relevant parts of BS7533: Part 10 and have made adjustments to the recommendations contained in those parts based upon the results of the testing of the Pietra Pave jointing material and my Finite Element analysis. By calculating stresses, strains and deflections using the Geostudio Finite Element program and by comparing those values with allowable values derived by the use of Transfer Functions which relate permissible stresses and strains to the amount of traffic expected to use a pavement, I have been able to produce revised pavement sections.

INCLUSION OF GEOGRIDS

I have also addressed the relevance of geogrids. The Tobermore trials, which I described in my permeable pavements design report showed that they add little to the longevity of pavements trafficked by Large Goods Vehicles (LGVs) in the case of subgrade CBRs of 5% and above.

The tables include headers which show how using a geogrid effectively lifts the ground conditions by 1% CBR, i.e. when using a geogrid on soils of 4% CBR or less the capping thickness is as for a 1% higher CBR subgrade. This means that the benefit of geogrids applies only for low CBR soils and the benefit increases with a decrease in CBR which maps correctly onto CIRIA geogrid guidance. This is an approach which the geogrid manufacturers would do well to replicate in all of their design guidance and fits better with the research than the approach currently proposed by geogrid manufacturers whereby a constant reduction in pavement thickness is allowed by the inclusion of a geogrid, irrespective of ground conditions.

DERIVATION OF PAVEMENT DESIGN SECTIONS

The following design sections have been developed by carrying out a Finite Element analysis with the purpose of establishing that they each provide sufficient protection to the underlying subgrade to endure that rutting will not develop. Also, those pavements which include DBM or HMB (C10 Lean Concrete) have been checked to ensure that fatigue cracking (DBM) or overstressing (HMB) will not occur within those materials.

These twin criteria have been checked by comparing the stresses and strains which the Finite Element analysis shows to develop in the subgrade and in the DBM/HMB with stresses and strains derived from equations often referred to as *Transfer Functions* which provide values of the stresses and strains which should not be exceeded within the subgrade and within the base. There are many Transfer Functions available. This is because they are empirical equations which have been derived from observations of the performance of pavements of known material properties. Different authoritative highway administrations, including the UK's Highways Agency have monitored the performance of their pavements and have thereby derived Transfer Functions appropriate to their own pavements.

I have selected the most widely used Transfer Functions. These are equations which were derived by the US Corps of Engineers. They have been applied by highways agencies in the US and the UK, by Federal Aviation Administration and in the British Ports Association manual for over 25 years and are considered to be well proven.

DETAILS OF FINITE ELEMENT ANALYSIS

I have used a linear elastic Finite Element (FE) computer program called GeoStudio to verify the suitability of each of the pavement sections which I list in the tables in the next section.

I have adopted the values shown in the following table in the Finite Element design verification exercise. The two values for Petra Pave are based upon the AECOM test results. AECOM established the Elastic Modulus of the jointing material to be approximately 11,000MPa. The two values shown in the table take this value into account and include the effect of the bedding material and the pavers themselves. In the case of sand bedding, the value used in the FE analysis is diminished to 6,000MPa because of the flexibility of the sand (300MPa) and in the case of the rigidly bedded Pietra Pave, it is enhanced to 20,000MPa by the stiffness of the rigid bedding material (30,000MPa).

MATERIAL	ELASTIC MODULUS (N/MM^2 OR MPA)	POISSON'S RATIO
Sand Bedded Pietra Pave	6,000	0.4
Rigidly Bedded Pietra Pave	20,000	0.2
Type 1 Granular Sub-base	400	0.3
Dense Bitumen Macadam 50 Penetration Bitumen	6,000	0.3
EME2 Asphalt*	14,000	0.15
C8/10 Concrete	35,000	0.15
C35 Concrete	30,000	0.15
Capping	150	0.35
5% CBR Subgrade	50	0.45

*** EME2 is high modulus asphalt recently introduced by The Highways Agency. I have used it in place of the more traditional DMB50 for those circumstances where the Finite Element analysis has showed that the use of DBM50 leads to excessive vertical strains within the subgrade.**

For each pavement section, I have assumed that the support provided by the subgrade is equivalent to a semi-infinite uniform material of stiffness modulus 50MPa. This is in line with a California Bearing Ratio (CBR) figure of 5%. The charts illustrate how the design section has to be modified in the case of pavements built over ground with a CBR of less than 5%. In the case of ground with a CBR in excess of 5%, the design should be as for 5% CBR ground, in line with normal highway design procedures.

In order to establish the design sections, I have used an axi-symmetric Finite Element analysis in which the pavement and the soil supporting it are represented by a series of circular components which each represent part of either the pavement or soil, as shown in the following Figure. These circular components are *Finite Elements*. In this Figure, I have removed a slice of the "cake" to illustrate the internal sub-division of the pavement and soil into its Finite Elements – the slice of cake is not removed during the calculations. A vehicle wheel load is shown as a circular patch in the centre of the model. In the case of pavements designed to sustain Large Goods Vehicles, I have used a 4 tonne (40kN) wheel load with a tyre contact pressure of

0.8MPa which represents the conventional standard axle condition as used in pavement design universally.

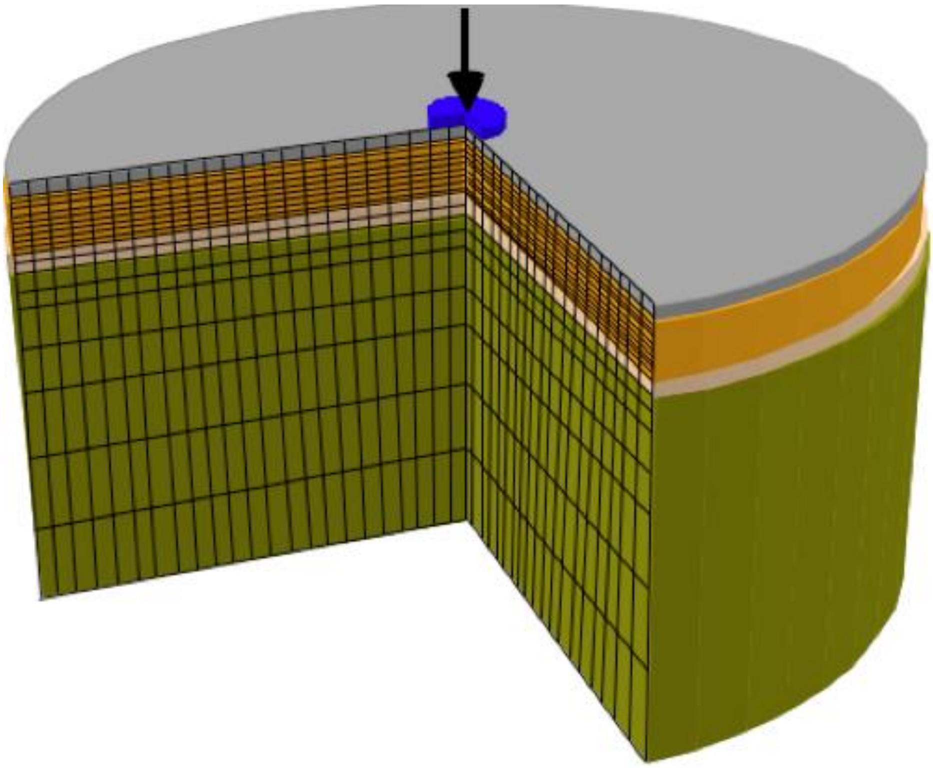
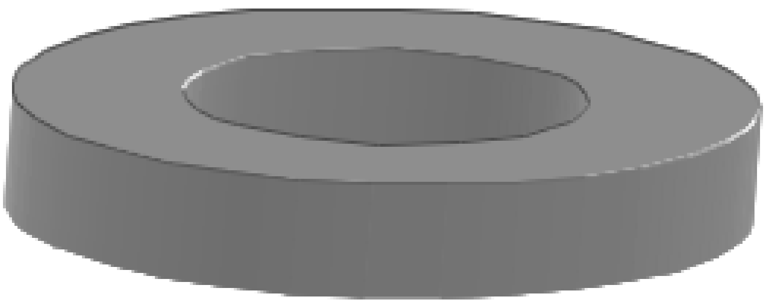


Illustration of the way in which a pavement is modelled using axi-symmetric Finite Elements.

The next Figure illustrates the shape of each element.



An axi-symmetric finite element has the three-dimensional shape shown

Providing the amount of pavement and soil modelled is sufficient to contain the entire deflected shape of the loaded pavement, the axi-symmetric Finite Element method is considered to represent a realistic assessment of the way in which the pavement and underlying soil develop stress and deflexion in response to a wheel load. I have modelled 6m diameter of pavement and 3m depth from the road surface to the boundary condition at the underside of the modelled zone. Over the last 25 years, I have found this size to provide accurate results.

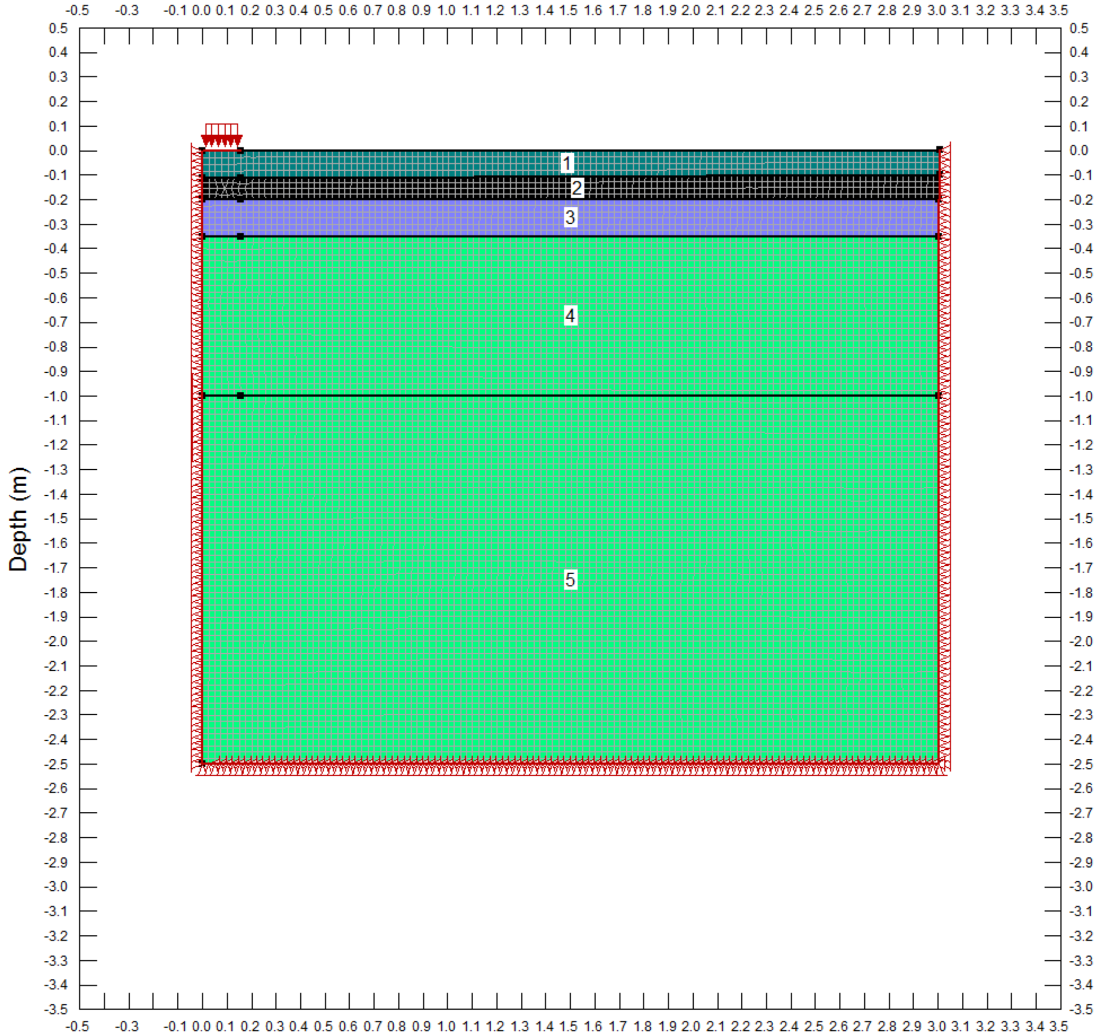
PROPOSED DESIGN SECTIONS FOR CONVENTIONAL PAVEMENTS

STRESSES, STRAINS AND DEFLECTIONS WITHIN PAVEMENTS

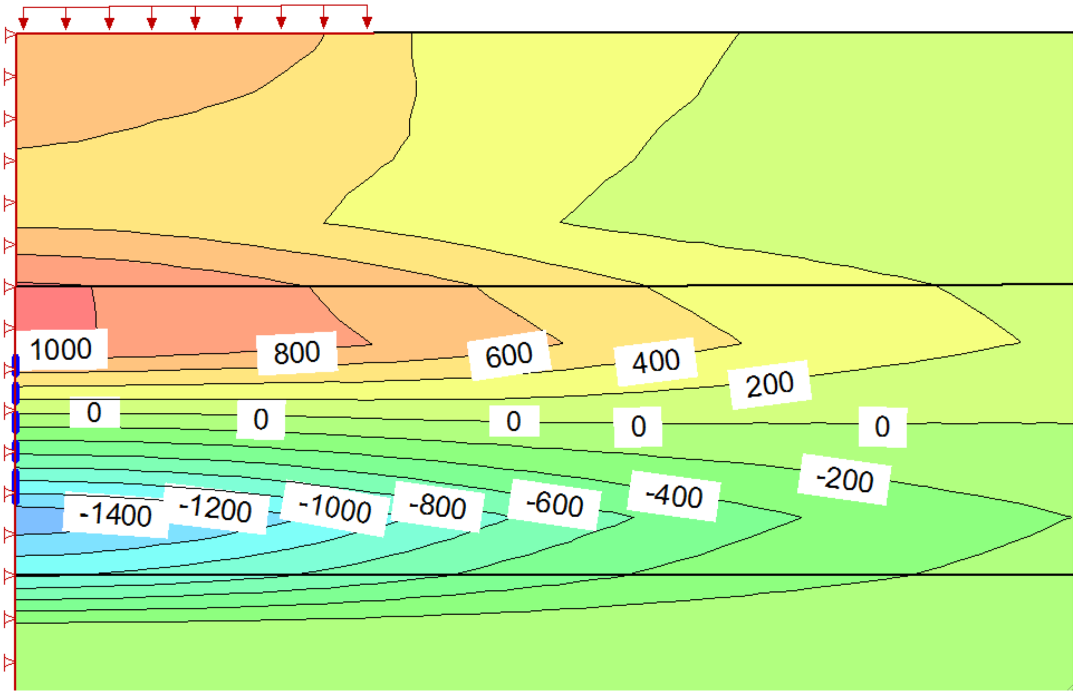
For each of the design cases, I have produced charts showing patterns of Vertical Deflections, Vertical Strains and either Horizontal Strains (for DBM where Horizontal Strain is the appropriate criterion) or Horizontal Stresses (for C10 lean concrete where Horizontal Stress is the appropriate criterion). I illustrate below typical charts for each of these properties of a loaded pavement. I have modelled a zone of pavement of diameter 6m and depth 3m because this covers the whole of the zone where stresses, strains and deflections have meaningful values. Each of the stress patterns shows part of the side of the side of the slice of cake near its upper centre. I have chosen to illustrate these limited parts of the modelled pavements because it is in these zones that the values of stresses, strains and deflections have their critical values, i.e. the values which need to be compared with allowable values as derived by a *Transfer Function*.

As well as producing charts illustrating the state of stress, strain and deflection within and below the pavement, GeoStudio also provides values of the critical properties. I have included these values in the tables of Finite Element output for each of the pavement sections modelled.

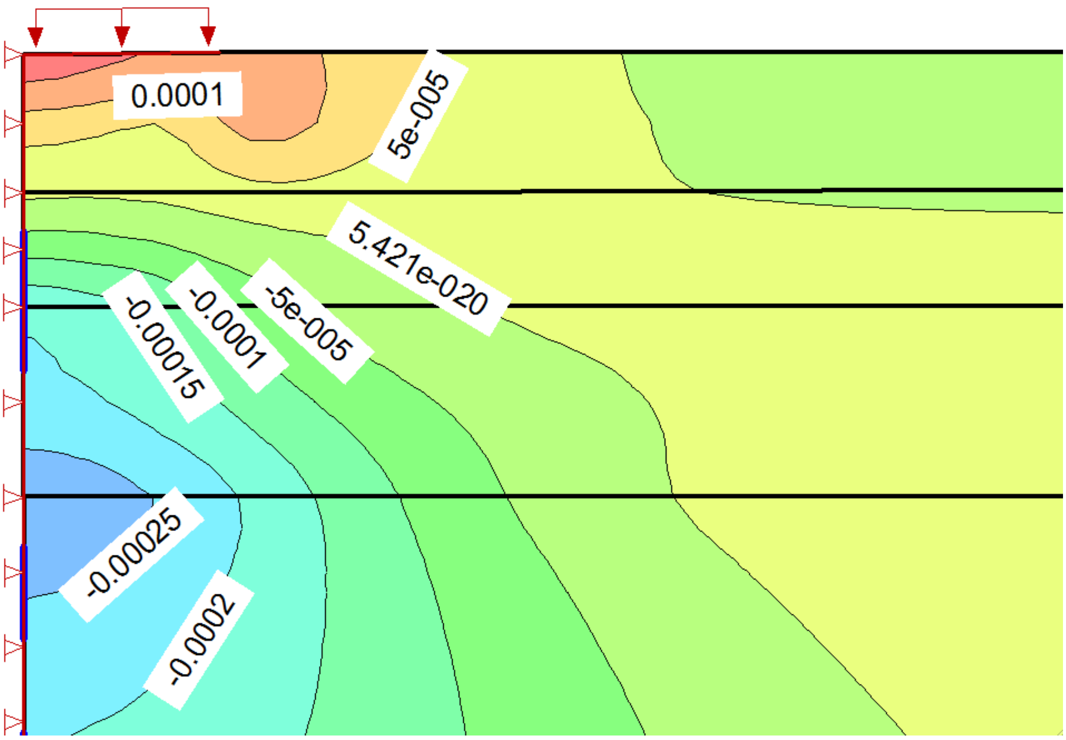
For each of the pavement sections modelled, I have included diagrams showing the model and the relevant contours in Appendix B.



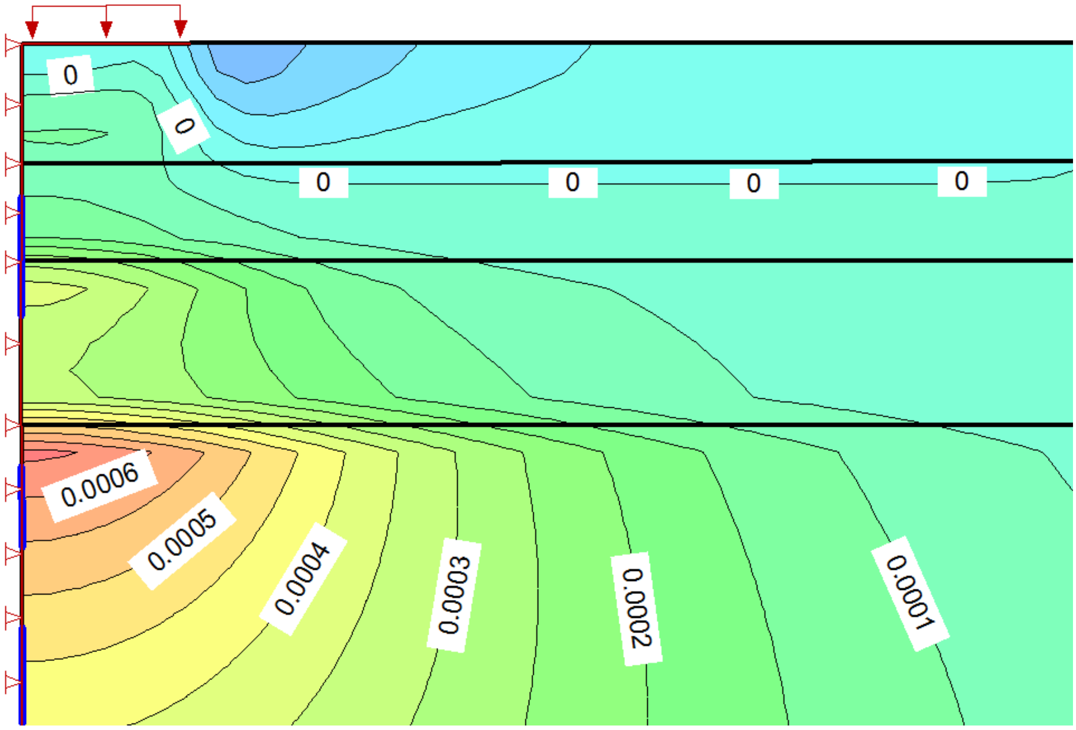
This diagram illustrates how the vertical slice of the "cake" is divided into pavement layers of radius 3m and total depth 3m. The downward arrows at top left represent the radius of the wheel patch. This diagram essentially shows the right hand half of the pavement. The left vertical side is the centre of the zone modeled.



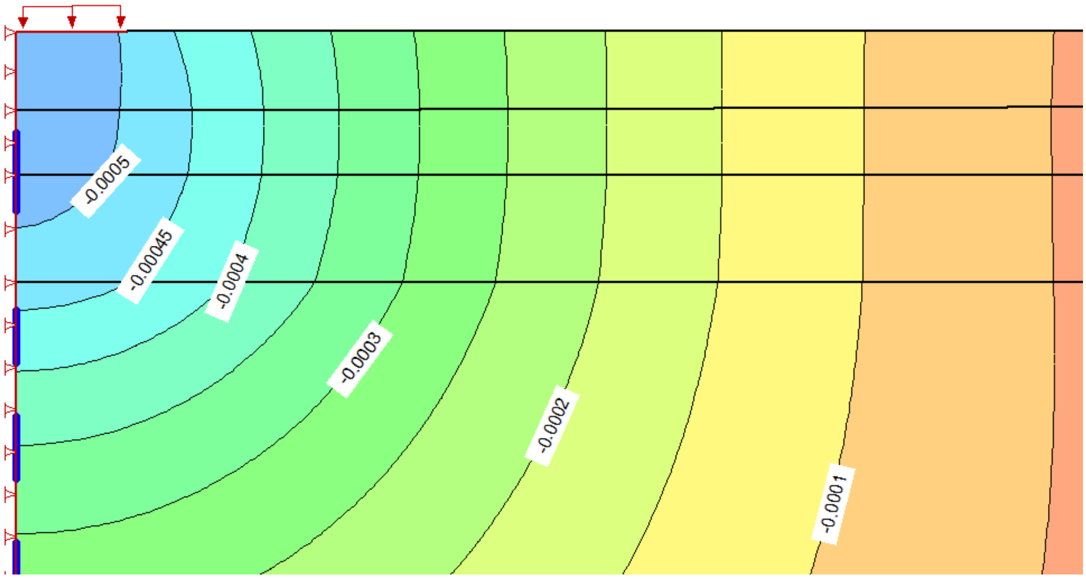
Typical pattern of Horizontal Stresses near the point of application of the wheel load (in kPa – divide by 1000 to obtain stresses in MPa). The contour shown as zero is the Neutral Axis. All of the material above the neutral axis is in compression and all of the material below is in tension as the CBM roadbase bends under the load at the top left of the diagram.



Typical pattern of Horizontal Strain as required for pavements which include a Dense Bitumen Macadam (DBM) roadbase. Horizontal Strain is the critical matter in selecting the thickness of DBM required.



Typical pattern of Vertical Strain. This is a critical property for the subgrade. The Vertical Compressive Strain in the subgrade has to be limited to a value depending upon the number of load repetitions for which the pavement is being designed.



Typical pattern of vertical displacements. It is important to assess the deflection of the surface of the pavement at the point of application of the wheel patch load. If this is too hight, then although the pavement may not fail structurally, the surface could be damaged and/or interlock could be lost.

DESIGN SECTIONS FOR PIETRA PAVE PAVEMENTS

The sections in the Table apply in the case of subgrades of 5% CBR or more.

For pavements over lower CBR values, include the following capping:
1% CBR 600mm capping or 300mm capping plus Geogrid
2% CBR 350mm capping or 225mm capping plus Geogrid
3% CBR 225mm capping or 150mm capping plus Geogrid
4% CBR 150mm capping or Geogrid

SETT SIZE CATEGORIES AS USED IN BS7533 PART 10 IV

CATEGORY	PLAN DIMENSIONS		MINIMUM DEPTHS		DESIGN JOINT WIDTH (mm)
	MAXIMUM WIDTH (mm)	MAXIMUM LENGTH (mm)	FULL SETTS (mm)	SHALLOW SETTS (mm)	
Size 1	50	100	50	—	6-10
Size 2	80	160	80	40	8-12
Size 3	100	200	100	50	8-12
Size 4	150	300	150 A)	75	10-15

PAVEMENT USE	EXISTING BS7533:10 SECTION FOR PAVEMENT SURFACED WITH SETTS	PIETRA PAVER PROPOSED DESIGN SECTION
Pedestrian and Domestic Driveways (BS7533 Part 10 IV)	UNBOUND SURFACE UNBOUND BASE Size 2 Full Sett 40mm Sand laying course 300mm Type 1 Sub-base material UNBOUND SURFACE RIGID BASE Size 1 Full Sett 40mm Sand laying course 90mm DBM50 110mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 1 Full Sett or Size 2 Shallow Sett 40mm moist or 30mm plastic bedding 40mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Pietra Pavers 40mm Sand laying course 150mm Type 1 Sub-base material UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 40mm DBM50 110mm Type 1 Sub-base material BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 25mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material
Cars & Light Vans (BS7533 Part 10 IV)	UNBOUND SURFACE UNBOUND BASE Size 2 Full Sett 40mm Sand laying course 300mm Type 1 Sub-base material UNBOUND SURFACE RIGID BASE Size 1 Full Sett 40mm Sand laying course 90mm DBM50	UNBOUND LAYING COURSE UNBOUND BASE Pietra Pavers 40mm Sand laying course 225mm Type 1 Sub-base material UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 70mm DBM50 110mm Type 1 Sub-base material

PAVEMENT USE	EXISTING BS7533:10 SECTION FOR PAVEMENT SURFACED WITH SETTS	PIETRA PAVER PROPOSED DESIGN SECTION
	110mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 1 Full Sett or Size 2 Shallow Sett 40mm moist or 30mm plastic bedding 40mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material	BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 35mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material
Traffic up to 7.5 tonne	UNBOUND SURFACE UNBOUND BASE Size 2 Full Sett 40mm Sand laying course 300mm Type 1 Sub-base material UNBOUND SURFACE RIGID BASE Size 1 Full Sett 40mm Sand laying course 90mm DBM50 110mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 1 Full Sett or Size 2 Shallow Sett 40mm moist or 30mm plastic bedding 40mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Pietra Pavers 40mm Sand laying course 300mm Type 1 Sub-base material UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 85mm DBM50 110mm Type 1 Sub-base material BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 40mm DBM50 or 100mm C8/10 110mm Type 1 Sub-base material
Emergency Large Goods Vehicles only (100 standard axles cumulative) (BS7533 Part 10 III)	UNBOUND SURFACE UNBOUND BASE Size 2 Full Sett 40mm Sand laying course 300mm Type 1 Sub-base material UNBOUND SURFACE RIGID BASE Size 2 Full Sett 40mm Sand laying course 120mm DBM50 225mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 2 Full Sett or Size 3 Shallow Sett 40mm moist or 30mm plastic bedding	UNBOUND LAYING COURSE UNBOUND BASE Pietra Pavers 40mm Sand laying course 450mm Type 1 Sub-base material UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 100mm DBM50 225mm Type 1 Sub-base material BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 75mm DBM50 or 100mm C8/10 150mm Type 1 Sub-base material

PROPOSED DESIGN SECTIONS FOR CONVENTIONAL PAVEMENTS

PAVEMENT USE	EXISTING BS7533:10 SECTION FOR PAVEMENT SURFACED WITH SETTS	PIETRA PAVER PROPOSED DESIGN SECTION
	200mm DBM50 or 150mm C8/10 150mm Type 1 Sub-base material	
One Large Goods Vehicle per week (0.015msa) (BS7533 Part 10 III)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Size 2 Full Sett 40mm Sand laying course 120mm DBM50 225mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 2 Full Sett or Size 3 Shallow Sett 40mm moist or 30mm plastic bedding 200mm DBM50 or 150mm C8/10 150mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 115mm DBM50 225mm Type 1 Sub-base material BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 90mm DBM50 or 100mm C8/10 150mm Type 1 Sub-base material
Ten Large Goods Vehicles per week (0.15msa) (BS7533 Part 10 III)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Size 2 Full Sett 40mm Sand laying course 120mm DBM50 225mm Type 1 Sub-base material BOUND SURFACE RIGID BASE Size 2 Full Sett or Size 3 Shallow Sett 40mm moist or 30mm plastic bedding 200mm DBM50 or 150mm C8/10 150mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm Sand laying course 125mm DBM50 225mm Type 1 Sub-base material BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 115mm DBM50 or 115mm C8/10 150mm Type 1 Sub-base material
100 Large Goods Vehicles per week (BS7533 Part 10 II)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Size 3 Full Sett 40mm Sand laying course 160mm DBM50 225mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Not applicable BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 130mm DBM50 or 130mm C8/10

PROPOSED DESIGN SECTIONS FOR CONVENTIONAL PAVEMENTS

PAVEMENT USE	EXISTING BS7533:10 SECTION FOR PAVEMENT SURFACED WITH SETTS	PIETRA PAVER PROPOSED DESIGN SECTION
	BOUND SURFACE RIGID BASE Size 2 Full Sett or Size 3 Shallow Sett 40mm moist or 30mm plastic bedding 200mm DBM50 or 200mm C8/10 150mm Type 1 Sub-base material	150mm Type 1 Sub-base material
1.5 to 4msa (BS7533 Part 10 I)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Not applicable BOUND SURFACE RIGID BASE Size 3 Full Sett or Size 4 Shallow Sett 40mm moist or 30mm plastic bedding 200mm DBM50 or 200mm C8/10 150mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Not applicable BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 145mm DBM50 or 145mm C8/10 150mm Type 1 Sub-base material
4 to 8 msa (BS7533 Part 10 IA)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Not applicable BOUND SURFACE RIGID BASE Size 4 Full Sett 40mm moist or 30mm plastic bedding 200mm DBM50 or 150mm PQC 150mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Not applicable BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 160mm DBM50 or 125mm PQC 150mm Type 1 Sub-base material
1000 Large Goods Vehicles per week (8-12msa) (BS7533 Part 10 IB)	UNBOUND SURFACE UNBOUND BASE Not applicable UNBOUND SURFACE RIGID BASE Not applicable BOUND SURFACE RIGID BASE Size 4 Full Sett with increased depth 40mm moist or 30mm plastic bedding 200mm DBM50 or 150mm PQC 150mm Type 1 Sub-base material	UNBOUND LAYING COURSE UNBOUND BASE Not applicable UNBOUND LAYING COURSE RIGID BASE Not applicable BOUND LAYING COURSE RIGID BASE Pietra Pavers 40mm moist or 30mm plastic bedding 175mm DBM50 or 140mm PQC 150mm Type 1 Sub-base material

PROPOSED DESIGN SECTIONS FOR CONVENTIONAL PAVEMENTS

SUBGRADE STRAIN TRANSFER FUNCTION

The following equation is the *Subgrade Strain Transfer Function*:

The Allowable Number of Repetitions and the vertical strain within the subgrade are related by the equation:

$$N = 10,000\left(\frac{A}{S_S}\right)^B$$

Where:

N = Number of Repetitions which the pavement can sustain (as established from Finite Element program)
A = 0.000247 + 0.000245.Log(M_r)
S_S = Vertical Strain at upper surface of subgrade
M_r = Resilient Modulus of Subgrade (psi)
B = 0.0658.$M_r^{0.559}$

The relationship between California Bearing Ratio, and Resilient Modulus for the designs being considered is as in Table 1 below.

Table 1. Relationship between California Bearing Ratio and Resilient Modulus

CALIFORNIA BEARING RATIO	RESILIENT MODULUS		VALUE OF CONSTANT *A*	VALUE OF CONSTANT *B*
	PSI	**N/mm²**		
1%	1,450	10	0.00102	3.85
2%	2,900	20	0.00110	5.67
3%	4,350	30	0.00114	7.11
4%	5,800	40	0.00117	8.56
5%	7,250	50	0.00119	9.47
20% **(Coarse Graded Aggregate or Capping)**	29,000	200		

Figure 2 below shows the relationship between vertical strain at the surface of the subgrade and the number of repetitions to failure (called “coverages” by CAA to distinguish the figure from aircraft passes). The points on figure 2 are individual pavements. The four slopes on Figure 2 refer to subgrades of modulus 4,500psi (uppermost line), 9,000psi (blue line), 15,000psi (yellow line) and 22,500psi (lowest line)respectively (3% CBR, 6% CBR, 10% CBR and 15% CBR).

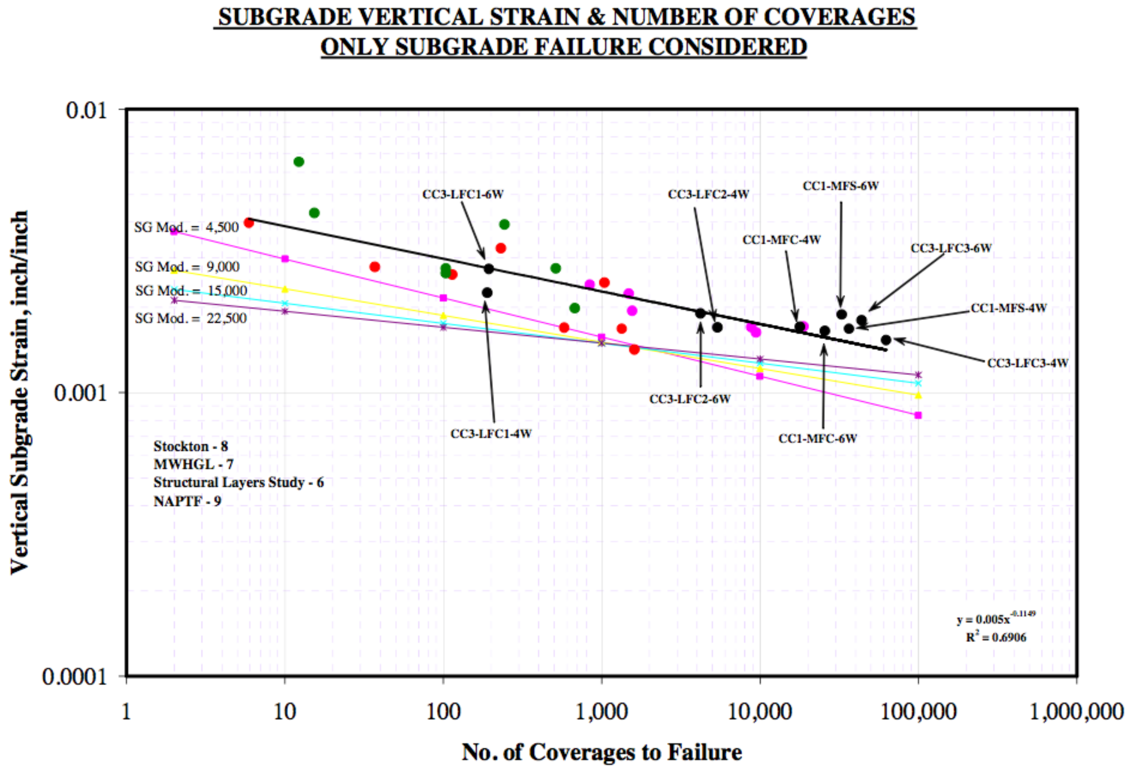
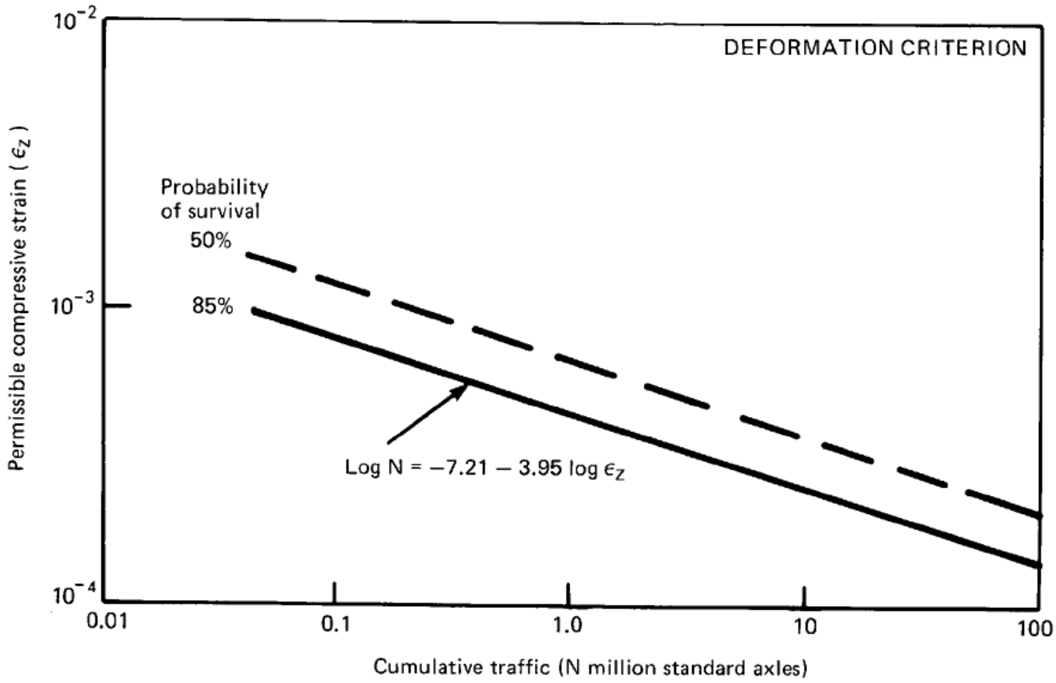


FIGURE 2 LEDFAA 1.2 failure model showing full-scale test data and model curves for four subgrade modulus values.

The figure below shows the relationship between number of repetitions and permissible subgrade strain as set out in TRL's Laboratory report LR1132 "The Structural Design of Bituminous Roads" (Powell, Potter, Mayhew & Nunn, 1984).



(b) Top of the subgrade

Fig. 4 Permissible strains induced by a standard 40kN wheel load at a pavement temperature of 20°C

The Following Table shows the allowable vertical strain values in the subgrade corresponding with the design traffic figures in this report.

NO. OF REPETITIONS	ALLOWABLE SUBGRADE VERTICAL STRAIN
100	0.0047
15,000	0.0013
150,000	0.00071
1,500,000	0.000377
4,000,000	0.000295
8,000,000	0.000265
12,000,000	0.000242

DENSE BITUMEN MACADAM STRAIN TRANSFER FUNCTION

The following equation is the A*sphalt Strain Transfer Function*:

The Allowable Number of Repetitions and the horizontal tensile strain within the asphalt are related by the equation:

The Allowable Number of Repetitions, *N* is obtained from:

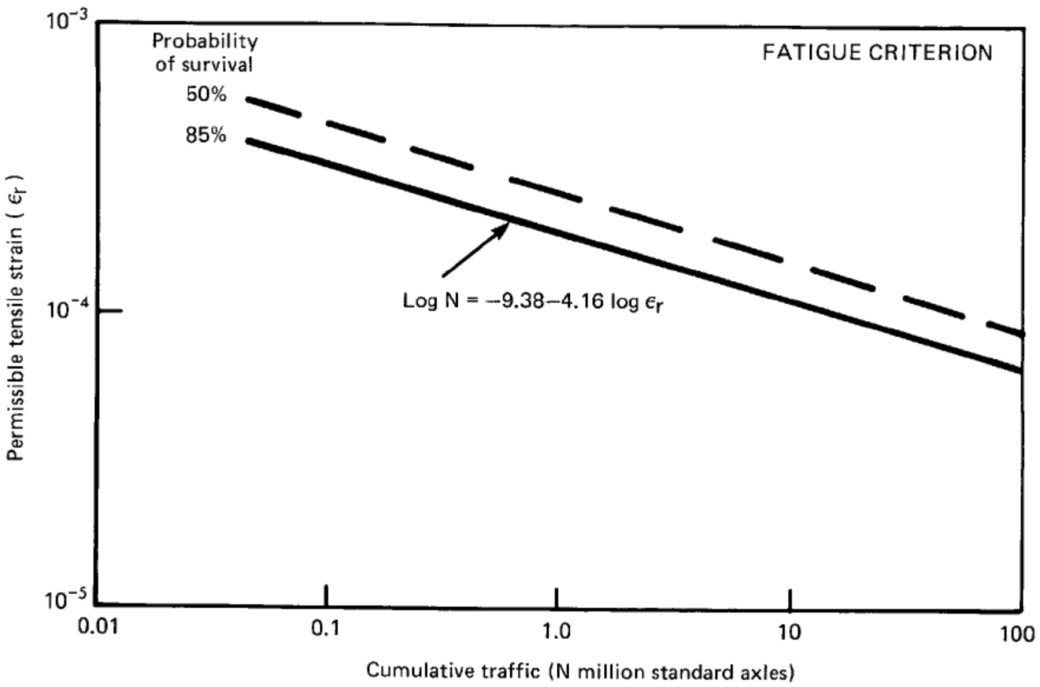
$$N = 10^x$$

Where:

N = Number of Repetitions which the pavement can sustain
$x = 2.68 - 5.\text{Log}(S_A) - 2.665\ \text{Log}(E)$
S_A = Horizontal Tensile Strain at underside of DBM (as established from Finite Element program)
E = Elastic Modulus of DBM (psi) (say 600,000psi or 4136N/mm^2) which means:
$x = 12.72 - 5.\text{Log}(S_A)$

The figure below shows the above relationship between number of repetitions and horizontal tensile strain (often referred to as "fatigue strain") as set out graphically for DBM in TRL's Laboratory Report LR1132 "The Structural Design of Bituminous Roads" (Powell, Potter, Mayhew & Nunn, 1984).

LR1132 uses a similar relationship to the above equation.



(a) Bottom of dense bitumen macadam roadbase

Using the above chart, LR1132 shows the following relationship between asphalt thickness and number of wheel patch repetitions.

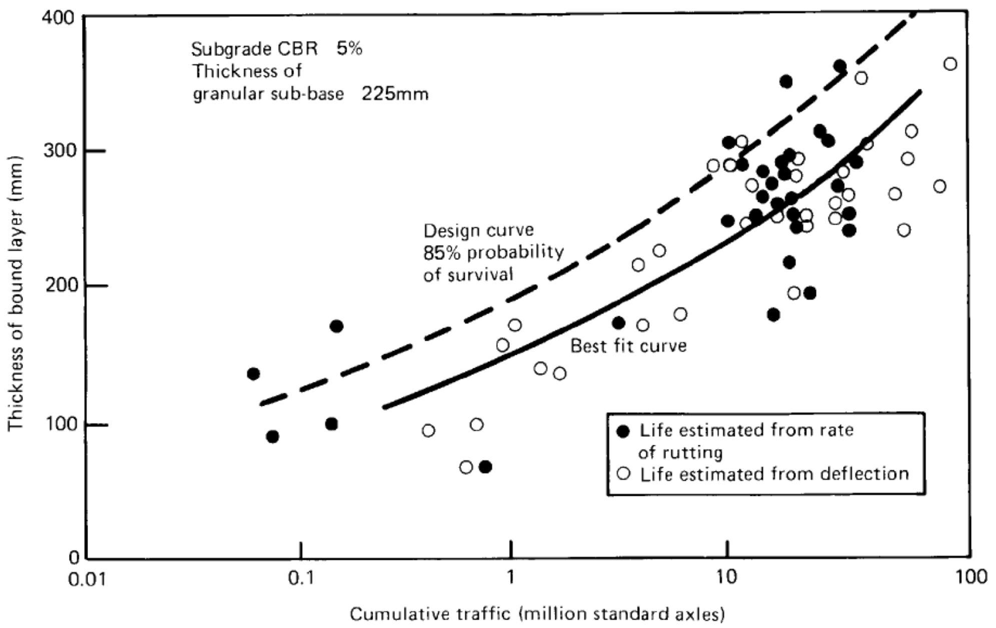


Fig. D1 Relation between thickness and life of experimental roads with dense bitumen macadam roadbase

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The following extract from TRL's LR1132 shows the actual strain relationships used by TRL which differ to a degree from FAA and BPA figures and which take into account the particular characteristics of Highways Agency's DBM. Note that the figures equate to DBM with 100 Penetration bitumen whereas it is now common to use 50 Penetration asphalt. This provides a degree of conservatism in design. For this reason, the FAA fatigue relationships shown in Figure 2 above are more appropriate and can be used in the validation of the design proposals.

17. APPENDIX E

INPUT DATA FOR THE DESIGN MODEL AND AN EXAMPLE OF APPLYING THE DESIGN METHOD

17.1 Data required for design models

To make best use of the design method, the structural properties of the pavement materials and subgrade must be known. The values assigned to each property to calculate critical strains in the standard designs are given below:

Bituminous material

Loading frequency	5 Hz
Equivalent temperature	20°C
Modulus of dense bitumen macadam (100 pen)	3.1 GPa
Modulus of hot rolled asphalt (50 pen)	3.5 GPa
Poisson's ratio	0.35

Fatigue criterion:

For dense bitumen macadam (100 pen) $\log N_f = -9.38 - 4.16 \log \epsilon_r$

For hot rolled asphalt (50 pen) $\log N_f = -9.78 - 4.32 \log \epsilon_r$

where N_f is the road life in standard axles and ϵ_r is the horizontal tensile strain at the underside of the bound layer under a standard wheel load.

Deformation criterion $\log N_d = -7.21 - 3.95 \log \epsilon_z$

where N_d is the life of road in standard axles and ϵ_z is the vertical compressive strain at the top of the subgrade under a standard wheel load.

The following Table shows the allowable vertical strain values in the subgrade corresponding with the design traffic figures in this report.

NO. OF REPETITIONS	ALLOWABLE ASPHALT HORIZONTAL STRAIN
100	0.0018
15,000	0.0005
150,000	0.0003
1,500,000	0.0002
4,000,000	0.00015
8,000,000	0.0001
12,000,000	0.00008

C10 LEAN CONCRETE (HYDRAULICALLY BOUND MATERIAL) STRESS TRANSFER FUNCTION

The US Portland Cement Association recommends the following equation relating Allowable Flexural Strength (sometimes referred to as Modulus of Rupture) to Compressive Stress:

$$F = 0.74\sqrt{C}$$

Where: F = Allowable Flexural Strength (MPa)
C = Compressive Strength (MPa)

Therefore, the Characteristic Flexural Strength of C10 concrete is 2.3MPa

The Highways Agency Transfer Function for cement bound materials is as follows:

$$Log\ N = 17.61 - 17.61(R)$$

Where:
R = Ratio of flexural stress to flexural strength
N = Number of stress repetitions

Using the above equation for C10 of Flexural Strength 2.3MPa leads to the following characteristic Flexural Strength Values:

NO. OF REPETITIONS	RATIO OF FLEXURAL STRESS TO FLEXURAL STRENGTH	ALLOWABLE FLEXURAL STRESS (MPA)
100	0.89	2.05
15,000	0.76	1.75
150,000	0.71	1.63
1,500,000	0.65	1.50
4,000,000	0.63	1.45
8,000,000	0.61	1.40
12,000,000	0.60	1.38

APPENDIX A

PART 10
OF
BS7533

BRITISH STANDARD

BS 7533-10:2004

Pavements constructed with clay, natural stone or concrete pavers —

Part 10: Guide for the structural design of trafficked pavements constructed of natural stone setts

ICS 93.080.20

British Standards

4 General design criteria

4.1 Basis of structural design

4.1.1 Design options

The design options provided in this standard include the following:

a) an unbound surface course laid upon a non-rigid unbound base; or
b) an unbound surface course laid upon a non-rigid base; or
c) a bound surface course laid upon a rigid base.

A design option for a bound surface course laid upon a non-rigid base is not provided since the stresses on the jointing material resulting from pavement deflection under traffic are such that durability cannot be assured.

NOTE 1 Guidance on the appropriateness of each design option is given in the relevant clause. Examples of the use of the design methods given in this standard are given in Annex A.

The designer should select the preferred surface course option and paving unit size then carry out a structural design for the traffic level and subgrade bearing strength of the site (see Clause **5** and Clause **6**).
If an acceptable design with the selected surface course is not possible or economic, an alternative surface course option should be selected and the design process repeated.
NOTE 2 For an unbound surface course laid upon a non-rigid base, the chosen thickness of the pavement is directly related to the number of commercial vehicles the pavement carries over its lifespan. For a bound surface course laid on a rigid base, the structural performance is affected by fatigue and one-off overload, or by repeated loading from
a small number of commercial vehicles, which can cause a failure in the jointing material itself or a failure of the bond between the jointing material and the unit.

4.1.2 Site categories

For the purposes of design, pavements should be categorized according to the commercial vehicular traffic assessment shown in Table 1.
Access ways to commercial and business premises and public buildings should be placed in site category I, II or III depending upon the estimate of the total commercial vehicular traffic likely to use the pavement
(see **6.3**).

Site category IV should only be selected where it can be ensured that no commercial vehicles use the pavement, e.g. where bollards have been installed.
In determining the site category, the use of the surface of the pavement by any construction traffic should be assessed and allowed for.

Table 1
Site categories for typical applications

Site category	**Standard axles per day**	**Typical applications**
IB IA	> 1 000 </= 1 000	Adopted highways and commercial developments used by a high number of commercial vehicles
I	</= 200	
II	</= 60	Adopted highways and other roads used by a moderate number of commercial vehicles Petrol station forecourts

		Pedestrian projects subjected to regular overrun of commercial vehicles
III	</= 5	Adopted highways and other roads used by a low number of commercial vehicles, e.g. cul-de-sac on a housing development Pedestrian projects subjected to occasional overrun of commercial vehicles Car parks receiving occasional commercial vehicular traffic Footways regularly overridden by commercial vehicular traffic
IV	0	Car parks receiving no commercial vehicular traffic Footways subjected to domestic vehicular crossover Private drives, paths, patios, hard landscaping Areas receiving pedestrian traffic only, e.g. school playgrounds

4.1.3 Special cases

Where dynamic and/or impact loading occurs, (e.g. on traffic calming ramps, or where a row of paving units is laid with its surface not flush with the surrounding pavement, or for sites subjected to braking or turning, or where there are steep hills) consideration should be given to introducing high horizontal tensile stresses into the pavement.
The structural design in terms of vertical loading should remain unchanged. However, before carrying out the design the number of standard axles using a site per day, determined in accordance with **6.3**, should be multiplied by two to allow for the higher horizontal tensile stresses. The site category of a site experiencing high horizontal tensile stresses should be determined in accordance with Table 1 after the value for the number of standard axles per day has been doubled.

Lateral edge restraints and intermediate restraints appropriate to the site category should be used (see BS 7533-7:2010, Annex D). Patterns should be arranged so that traffic does not run along continuous joints.
A combination of the following design options should be considered so that the site is able to resist the higher tensile stresses:
a) A paving unit type and size that offers higher loading capacity in the highly stressed area.
b) A laying pattern that increases interlock between the elements in unbound paving, e.g. arc patterns.
c) An increased frequency of lateral edge and intermediate restraint.
d) Where the standard axles are >200 and <1 000, size 4 full sett should be used.
e) Where the standard axles are >1 000 and the depth of the sett should be at least 20% greater than the width.

4.2 Skid resistance and abrasion resistance

The slip/skid resistance of the surface of natural stone setts should be determined to ensure adequate safety against skidding and slipping when new or in service. Guidance on the determination of the unpolished slip resistance value is given in BS 7932.

PROPOSED DESIGN SECTIONS FOR CONVENTIONAL PAVEMENTS

The abrasion resistance of the surface of natural stone setts should be determined in accordance with BS EN 1342 to ensure durability and the performance of the surface.

5 Materials

5.1 Foundation materials

In unbound pavement construction, the successful performance of the sub-base and/or base, bedding layer and jointing materials are dependent upon compaction being undertaken at critical moisture contents. In rigid bound pavement construction, the successful performance of the sub-base, base, bedding layer and jointing materials are dependent on achieving a specified strength and stiffness. The recommendations given in **5.2**, **5.3**, **5.4** and **5.5** for the materials used in the foundation of the pavements reflect this distinction.
Pavements in site categories II and III, where the overall design thickness is thin, may be constructed over frost-susceptible soils and may require the overall thickness of non frost-susceptible material to be increased to a value suitable for the locality (see also **6.1**).

5.2 Sub-bases

Sub-bases for both non-rigid and rigid pavements should be constructed from Type 1 sub-base in accordance with Clause 802 of the *Highways Agency's Specification for Highway Works* [1].

5.3 Base materials

For non-rigid unbound base (see Table 6), Type 1 sub-base in accordance with the appropriate clauses of the *Highways Agency's Specification for Highway Works* [1] should be used.
NOTE 1 Sub-base materials conforming to Clause 804 (Type 2) is inappropriate.

NOTE 2 A non-rigid unbound base layer can be the same layer as the sub-base if no separate base is provided.

In unbound systems, designers should take into account the requirement for water permeability of the sub-base.
For non-rigid base (see Table 6), any of the following binder course mixtures specified in BS EN 13108-1 should be used:

a) 0/20 mm size open graded binder course with bitumen grade 40/60 pen;
b) 0/20 mm AC 20 (DBM) 40/60 designed binder course;

c) 0/20 mm AC 20 (DBM) 100/150 recipe binder course for site category III and IV only.

For rigid base (see Table 7) comprising of pavement quality concrete (PQC), the material should conform to BS EN 13877-1 concrete strength class 32/40.
For rigid base (see Table 7) any of the following binder course mixtures specified in BS EN 13108-1 should be used:

1) 0/20 mm AC 20 (DBM) 100/150 designed binder course for site categories III and IV;
2) 0/20 mm AC 20 (DBM) 40/60 recipe binder course for site categories I, II, III and IV.

For non-rigid base (see Table 6) and rigid base
(see Table 7) comprising cement bound granular material (CBM), the concrete should have a minimum compressive strength of 15 N/mm^2 when measured in accordance with BS 7533-7. A non-rigid bound or rigid base layer should be water permeable to allow the free drainage of water from the bedding layer. Where dense material is used, adequate falls and suitable perforation to provide adequate permeability at the base should be provided.

NOTE 3 In unbound construction it is important that the bedding layer material does not become saturated in service.

5.4 Bedding layer material

5.4.1 Unbound surface course

The bedding layer material used in unbound construction should conform to the recommendations for sawn and cropped setts given in BS 7533-7:2010, **C.1**.
Fine aggregate material for bedding layers used in unbound construction should be the same as the jointing material (see **5.6**).

5.4.2 Bound surface course

The bedding layer material used in bound construction should conform to the recommendations for fine bedding concrete specified in
BS 7533-7:2010, **C.2.1** and BS 7533-4:2006, **5.4.4.2**.

5.5 Surface course materials

5.5.1 General

Setts should conform to BS EN 1342 and may:

a) be sawn on all six sides;

b) have sawn edges and a cropped or riven upper and/or lower surface;
c) have cropped or riven edges and a sawn upper and/or lower surface; and/or
d) be cropped on all six sides.

The deviation from nominal thickness should be in accordance with Class 2 of BS EN 1342:2001, Table 2. Freeze–thaw resistance should be in accordance with Class 1 of BS EN 1342:2001, Table 4.
BS EN 1342 requires the supplier to declare the value of compressive strength.
Depending upon the application, BS EN 1342 may require abrasion resistance and slip/skid resistance of setts to be declared (see 4.2).
For the purposes of design, the size of setts should be classified as given in Table 2. The depth of the sett is a minimum. Setts with a greater depth may be used if required [see **4.1.3**e)].

Table 2
Sett size categories

Category	**Plan dimensions**		**Min. depths**		**Design joint width** mm
	Max. width mm	**Max. length** mm	**Full setts** mm	**Shallow setts** mm	
Size 1	50	100	50	—	6-10
Size 2	80	160	80	40	8-12
Size 3	100	200	100	50	8-12
Size 4	150	300	150 [A)]	75	10-15

NOTE To calculate the minimum thickness of stone setts having lengths greater than stated; use the appropriate equation in BS EN 1341:2001, Annex B.
[A)] Setts with a increased depth have a minimum depth of 180 mm.

5.5.2 Sawn setts

Where sawn sett dimensions fall within the dimensional tolerances specified for clay pavers in BS EN 1344 and concrete paving blocks
in BS EN 1338, generally ±2 mm on plan dimensions, and can be laid to achieve the required degree of interlock, then they should be designed as a flexible surface as described in BS 7533-1 and BS 7533-2. This allows the material to be used in a higher category of loading (see Table 1 and Clause **6**).

Where sawn side setts are used for an unbound surface course, the side faces should be textured, i.e. rough sawn, to ensure good friction characteristics between the setts and the fine aggregate jointing material.
Where sawn side setts are used for a bound surface course, the side faces should be cleaned, i.e. pressure washed or scrubbed, to ensure good adhesion between the setts and the jointing and bedding concrete. Where jointing and bedding concrete is used, the level of adhesion should be tested in accordance with BS 7533-7.

5.6 Jointing materials

5.6.1 Unbound surface course

Jointing materials for an unbound surface course should be selected in accordance with BS 7533-7:2010, **C.1**.
NOTE Stabilized aggregates which employ a visco-elastic binder might be suitable for site category IV and may be used at the discretion of the specifier using the design criteria for unbound construction.

5.6.2 Bound surface course

The compressive strength of jointing materials for a bound surface course should be selected from Table 3 and conform to BS 7533-7:2010, **C.2.2**. Jointing materials with compressive strengths of 25 N/mm^2 and 40 N/mm^2 should conform to the additional jointing mortar recommendations given in BS 7533-7:2010, **C.2**.

Site category (see Table 1)	**Min. sett size category** (see Table 2 and **4.1.3**)		**Min. concrete block paving thickness** mm	**Bedding mortar designation according to BS 7533-7**	**Compressive strength of the joint** N/mm^2
	Shallow setts	**Full setts**			
IA (special case)	—	Size 4 with increased depth	—	Type B	40
IB (special case)	—	Size 4	—	Type B	40
I	Size 4	Size 3 Size 4	80 —	Type B Type A	40 40
II	Size 3	Size 2 Size 3 Size 4	80 — —	Type B Type A Type A	40 40 25
III	Size 3	Size 1 Size 3	50 80	Type B Type A	40 25
IV	Size 2	— Size 1	— 50	Type B Type A	40 25

6 Design

6.1 Subgrade assessment

The design should be based upon an assessment of the subgrade bearing strength, which is described as the California Bearing Ratio (CBR). The weaker the subgrade, the stronger the pavement required.
The design CBR should be obtained by measuring the plasticity index or defining the material description of the subgrade and then consulting Table 4.
NOTE 1 BS 7533-1:2001, ***5.1*** *gives further recommendations on the assessment of subgrade bearing strength.*

Table 4
CBR values for different material

Type of soil	**Plasticity index**	**Estimated CBR** %
Heavy clay	70 60 50 40 30	2 2 2 3 4
Silty clay	20	5
Sandy clay	10	5
Silt	Not applicable	1
Sand poorly graded	Not applicable	20 (7) [A)]
Sand well graded	Not applicable	40 (10) [A)]
Sandy gravel	Not applicable	60 (15) [A)]

[A)] The bracketed figures to be considered if these materials are likely to become saturated in service.
Table 4 is intended for use where the water table is 300 mm or more below formation level. In other conditions, specialist advice should be sought.

Effective subgrade drainage should be considered during the design procedure since this can have a significant effect on long-term CBR values.
NOTE 2 Filter drains set at the appropriate level and discharging to a satisfactory outfall or main drainage system have been found to perform satisfactorily.

On sites where the CBR varies from place to place, the lowest recorded values should be used or appropriate designs should be provided for different parts of the site using the lowest CBR recorded in each part.
Soft spots should be removed, and replaced with material having an appropriate CBR.

Care should be taken in the interpretation of site investigation data. In the case of subgrades, where strength is a function of their moisture content, the in-service strength can be much lower than the recorded values. Care should also be taken in using CBR values measured in summer because artificially high figures can be obtained due to dryness of the soil.
For site category IV loading only (see Table 1), subgrade strength should be estimated by carrying out the field test given in Annex B after the initial compaction of the trimmed ground.

6.2 Foundation thickness

Foundation thickness should be in accordance with Table 5, Table 6 and Table 7 for the different site categories.

Table 5
Foundation thickness and sett type – Unbound surface course, non-rigid unbound base

Site category	Min. compacted sub-base/unbound base thickness mm					Nominal compacted bedding layer thickness mm	Min. sett size category A)
	Design CBR						
	2%	3%	4%	5%	6%		
I, IA and IB	Not applicable					Not applicable	Not applicable
II	Not applicable					40	Size 3 – Full sett
III	500	450	375	300	250	40	Size 2 – Full sett
A) Sett size categories are given in Table 2.							

Table 6
Foundation thickness and sett type – Unbound surface course, non-rigid base

Site category	Min. compacted sub-base thickness mm					Nominal compacted thickness mm		Min. sett size category A)
	Design CBR					Bituminous, asphaltic and cement bound base	Bedding layer	
	2%	3%	4%	5%	6%			
I, IA and IB	Not applicable					Not applicable		Not applicable
II	300	275	250	225	175	160	40	Size 3 – Full sett
III	300	275	250	225	175	120	40	Size 2 – Full sett
IV	300	250	200	110	110	Not applicable	40	Size 1 – Full sett
A) Sett size categories are given in Table 2.								

Table 7
Foundation thickness and sett type – Bound surface course, rigid base

Site category	Min. compacted sub-base thickness mm					Nominal compacted thickness mm		Min. sett size category
	Design CBR					Bituminous, asphaltic and cement bound base	Cement bound (CBM) concrete (PQC)	
	2%	3%	4%	5%	6%			
IA (special case)	450	350	250	150	150	200	150 PQC	Size 4 - Full sett with increased depth
IB (special case)	450	350	250	150	150	200	150 PQC	Size 4 - Full sett
I	450	350	250	150	150	200	200 CBM	Size 3 - Full

						Not applicable	150 PQC	sett Size 4 - Shallow sett
II	300	275	250	150	150	200 Not applicable	200 CBM 150 PQC	Size 2 - Full sett Size 3 - Shallow sett
III	300	275	250	150	150	200 Not applicable Not applicable	150 CBM 150 PQC 150 PQC	Size 2 - Full sett Size 3 - Shallow sett Size 1 - Full sett
IV	300	250	200	110	110	40 Not applicable	100 CBM 120 PQC	Size 1 - Full sett Size 2 - Shallow sett
The bedding layer thickness after sett compaction should be 40 mm for moist bedding and 30 mm for plastic bedding in accordance with BS 7533-7:2010, **8.5.1**.								

6.3 Evaluation of traffic

The design for both non-rigid and rigid pavement construction should take into account the cumulative traffic the pavement has to carry, including construction traffic, measured in terms of the number of standard axles per day.
The type of commercial vehicles using the pavement will be mixed. Therefore, the number of standard axles per day should be determined by estimating the daily amount of each type of commercial vehicle using the pavement and then converting these figures to standard axles using the conversion factors given in Table 8.

The potential for growth of traffic over the intended design life of the pavement should be considered.
The design for both unbound and bound pavement construction should also take account of channelized traffic or dynamic/impact loading if applicable (see **4.1.3**). In the case of a bound surface course, a one-off overload can cause failure and should be taken into account in the design.
With an unbound surface course it can be necessary to reset the paving units during the life of a pavement. This can be a result of displacement of the bedding layer material and is not necessarily an indication of pavement failure.

Table 8
Standard axles per commercial vehicle

Vehicle type	**Conversion factor**
Buses and coaches	2.6
2 axle rigid	0.4
3 axle rigid	2.3
3 axle articulated	1.7
4 axle rigid	3.0
4 axle articulated	1.7
5 axle articulated	2.9
6 axles or more	3.7

NOTE For more details of the traffic calculation see HD24/06 [2].

6.4 Structural design

6.4.1 Foundation design – Unbound surface course

The contribution of an unbound surface course to the structural strength of the pavement as a whole can be quite small. It is, however, important that the surface course provides a stable and durable layer by the correct selection of sett size and correct installation.
Where an unbound surface course is formed from setts sawn on all edges these should be laid on an unbound bedding course, bedded down using a vibrating compactor and jointed with dry fine aggregate in accordance with BS 7533-7.
Where an unbound surface course is formed from cropped setts, these should be laid and jointed with crushed rock fines in accordance with BS 7533-7.
It is important that the bedding layer material does not become saturated in service. This is normally achieved using an unbound base. However, where a bound base is necessary it should be porous or have drainage provided, e.g. by forming holes to remove water.
Having assessed the site category for the application (Table 1) and
the design CBR (Table 4), the designer should use Table 5 to select the thickness for each pavement layer where an unbound base is used
or Table 6 to select the thickness of each pavement layer where a non-rigid base is used.
The sett size category should be appropriate to the site category and type of base and should be in accordance with Table 5, Table 6 or Table 7.
NOTE The thickness of a sub-base makes no allowance for it to be used as a site access way during construction.

Under adverse weather conditions, or for CBRs of 3% or less, the use of a geotextile separating membrane beneath the sub-base is recommended.
For CBRs of less than 2%, specialist advice should be sought about what would be an appropriate pavement foundation design.
On frost-susceptible soils the total construction thickness should be the minimum recommended for the site location, in cases of doubt a minimum of 450 mm of non frost-susceptible material should be used.

6.4.2 Foundation design – Bound surface course

The foundation design for a bound surface course should be irrespective of paving unit size and type.
The thickness of sub-base and rigid base should be selected from Table 7 depending upon site category (see Table 1).
NOTE The thickness of a sub-base makes no allowance for it to be used as a site access way during construction.

Under adverse weather conditions, or for CBRs of 3% or less, a geotextile separating membrane beneath the sub-base is recommended.
For CBRs of less than 2%, specialist advice should be sought on an appropriate pavement foundation design.
On frost-susceptible soils, the total construction thickness should be the minimum recommended for the site location, in cases of doubt a minimum of 450 mm of non frost-susceptible material should be used.

7 Preparation and construction

The subgrade, sub-base and base should be prepared in accordance with BS 7533-7:2010, Clause **5**. The bedding layer and surface of the pavement should be constructed in accordance with BS 7533-7.
The surface should be constructed in accordance BS 7533-7:2010, Annex A.

8 Overlay design

Where an existing part-worn pavement is to be overlaid, then the design should be undertaken by using the component overlay design method given in BS 7533-1.

Annex A (informative) Worked examples

A.1 Example A

A.1.1 Background

A new development wishes to place small setts in a central square, which is accessible to cars and commercial vehicles for delivery to domestic premises only. The architect is looking for a rough finish and would like an arc pattern.
A site investigation shows that clay soil is present and the testing of samples predicts a foundation CBR of 4%.

A.1.2 Design process

A.1.2.1 Surface selection

The architect prefers setts, size 1 or size 2 (see Table 2).

A.1.2.2 Traffic assessment

The site is to be designated site category III as defined in Table 1. For this site, two equally acceptable design options are available:

a) an unbound surface course design (see **A.1.2.3**); or
b) a bound surface course design (see **A.1.2.4**).

The choice between the two designs may be made on aesthetic grounds, providing that adequate slip/skid resistance and abrasion resistance is demonstrated.

A.1.2.3 Unbound surface course design

A non-rigid unbound base is not appropriate because of the likelihood of commercial vehicles and the low strength of the subgrade (see Table 5).
However, for site category III, Table 6 allows the selection of non-rigid base that has a sub-base thickness of 250 mm with 120 mm of bitumen bound or cement bound base.
Recommendations and guidance on foundation materials are given in Clause **5**.

For site category III, Table 6 permits the use of setts of size 2 full setts. Therefore, in accordance with the architect's preferences, setts of size 2 are permitted.

A.1.2.4 Bound surface course design

From Table 7, for site category III, the sub-base thickness needs to be 250 mm with 200 mm of bitumen bound or 150 mm of cement bound base. Recommendations and guidance on foundation materials are given in Clause **5**.
For site category III, Table 3 and Table 7 permit the use of a size 2 full setts for this type of base. Therefore, in accordance with the architect's preferences, size 2 full setts with bedding mortar designation Type B together with a design joint compressive strength of 40 N/mm^2 are permitted.

A.1.2.5 Alternative rigid surface design

From Table 7, for site category III, the sub-base thickness needs to be 250 mm with 150 mm of pavement quality concrete base. Recommendations and guidance on foundation materials are given in Clause **5**.
For site category III, Table 3 and Table 7 permit the use of size 1 full setts with bedding mortar designation Type B together with a design joint compressive strength of 40 N/mm^2.

A.2 Example B

A.2.1 Background

An area of stone paving has been proposed as part of a town centre improvement. It will be widely used by buses and delivery vehicles though cars will be excluded for most of the day. A site investigation was carried out and the foundation CBR was predicted to be 10%.

A.2.2 Design process

A.2.2.1 Surface selection

The designer prefers to use large setts on aesthetic grounds (see Table 2).

A.2.2.2 Traffic assessment

An estimate of the number of commercial vehicles on site is necessary. Therefore, a one day count of the number and type of commercial vehicles was organized. It was estimated, using the conversion factors in Table 8, that there were likely to be more than 60 but less than 200 standard axles per day using any part of the surface of the site. The site is to be designated site category I as defined in Table 1.
For this site two equally acceptable design options are available (see **6.4**), providing adequate slip/skid resistance and abrasion resistance is demonstrated.

A.2.2.3 Bound surface course design

From Table 7, the sub-base thickness for site category I is 150 mm with 200 mm of bituminous, asphaltic or cement bound granular material .
In accordance with the designer's preferences, for site category I, Table 3 and Table 7 permit the use of a size 3 full sett with bedding mortar designation Type B or size 4 full sett with bedding mortar designation Type A, together with a design joint compressive strength of 40 N/mm^2.

A.2.2.4 Alternative bound surface course design

From Table 7, the sub-base thickness for site category I is 150 mm with 150 mm of pavement quality concrete base.
In accordance with the designer's preferences, for site category I, Table 3 and Table 7 permit the use of a size 4 shallow sett with bedding mortar designation Type B together with a design joint compressive strength of 40 N/mm^2.

Annex B (informative) Identification of materials and CBR values using a simple field test
Table B.1 provides a method of identification for materials and CBR values using a simple field test.

Table B.1
Identification of materials and CBR values

Rock or soil		Simple field test	CBR %	Comments
Type	**Condition**			
Rock	Hard	Requires mechanical pick for excavation	>5	
Sand Gravel	Compact	50 mm, square peg hard to drive in 150 mm	>5	
Clay Sandy clay	Stiff	Cannot be moulded by fingers Need pick for excavation	5–2	
Clay Sandy clay	Firm	Can be moulded by fingers Need spade for excavation	5–2	
Sand Silty clay Clayey sand	Loose	Dry lumps easily broken down 50 mm, square peg driven in easily	2	
Silt Sandy clay Silty clay Clay	Soft	Can easily be moulded by fingers	<2	
Silt Sandy clay Silty Clay Clay	Very soft	Exudes between fingers when squeezed	Refer to specialist advice	

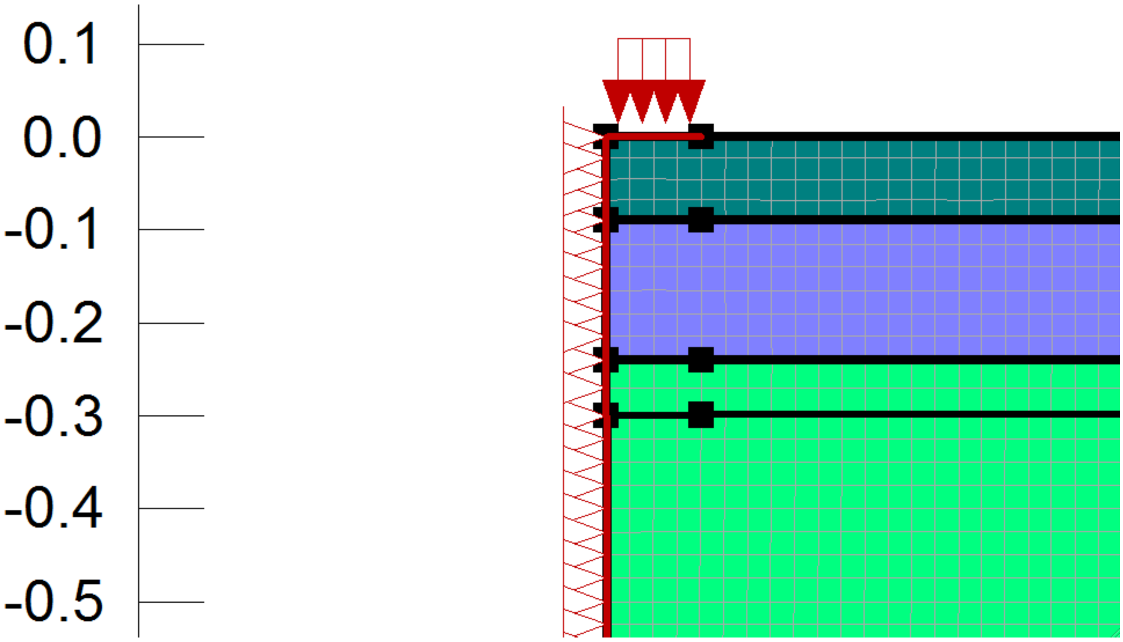
NOTE 1 This Table is based on the principles given in BS 8103-1.
NOTE 2 The CBR of the rock or soil is significantly affected by moisture content.

APPENDIX B

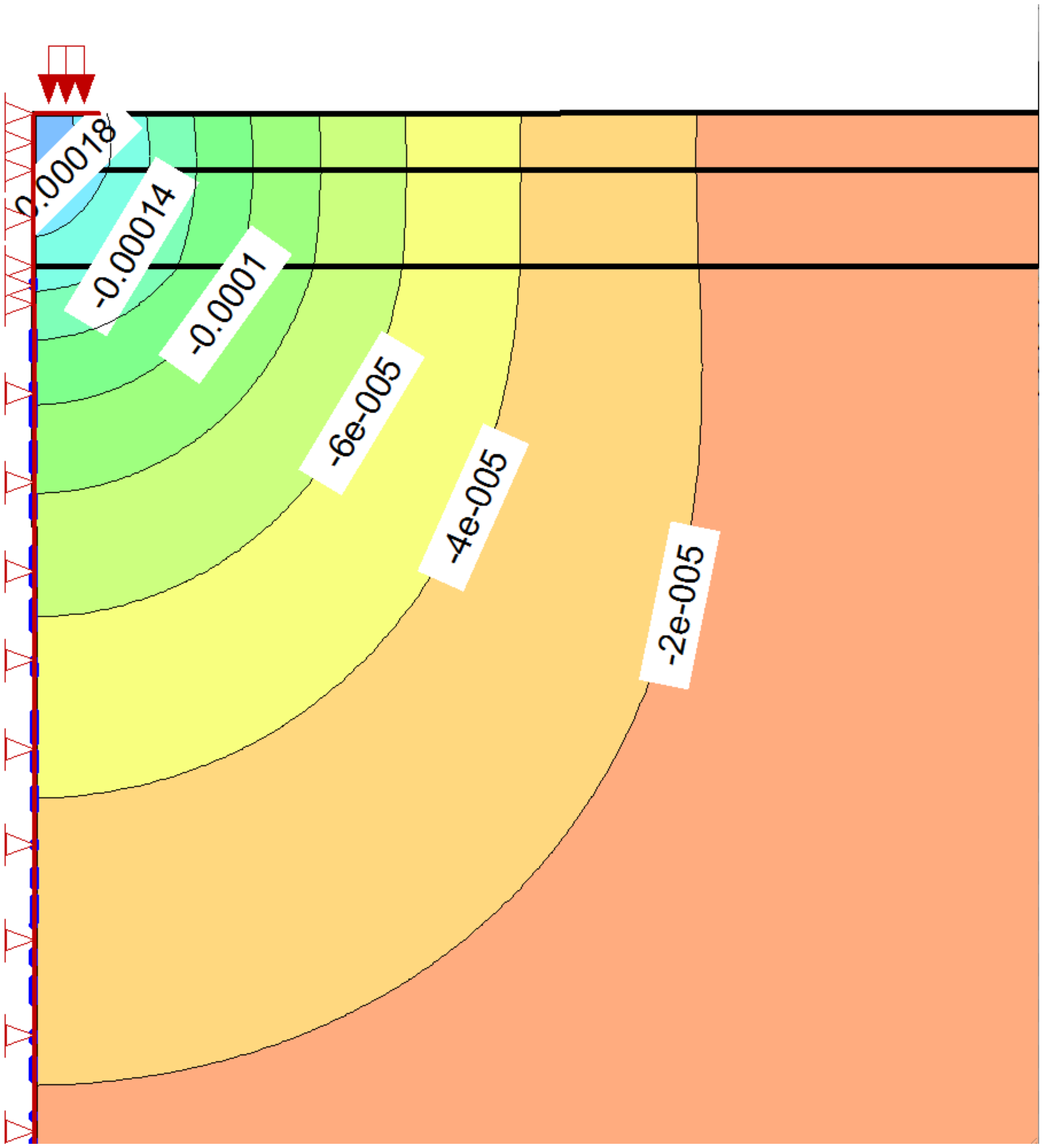
FINITE ELEMENT CONTOUR DIAGRAMS

UNBOUND SURFACE UNBOUND BASE PIETRA PAVE PAVEMENTS PEDESTRIAN AND DOMESTIC DRIVEWAYS

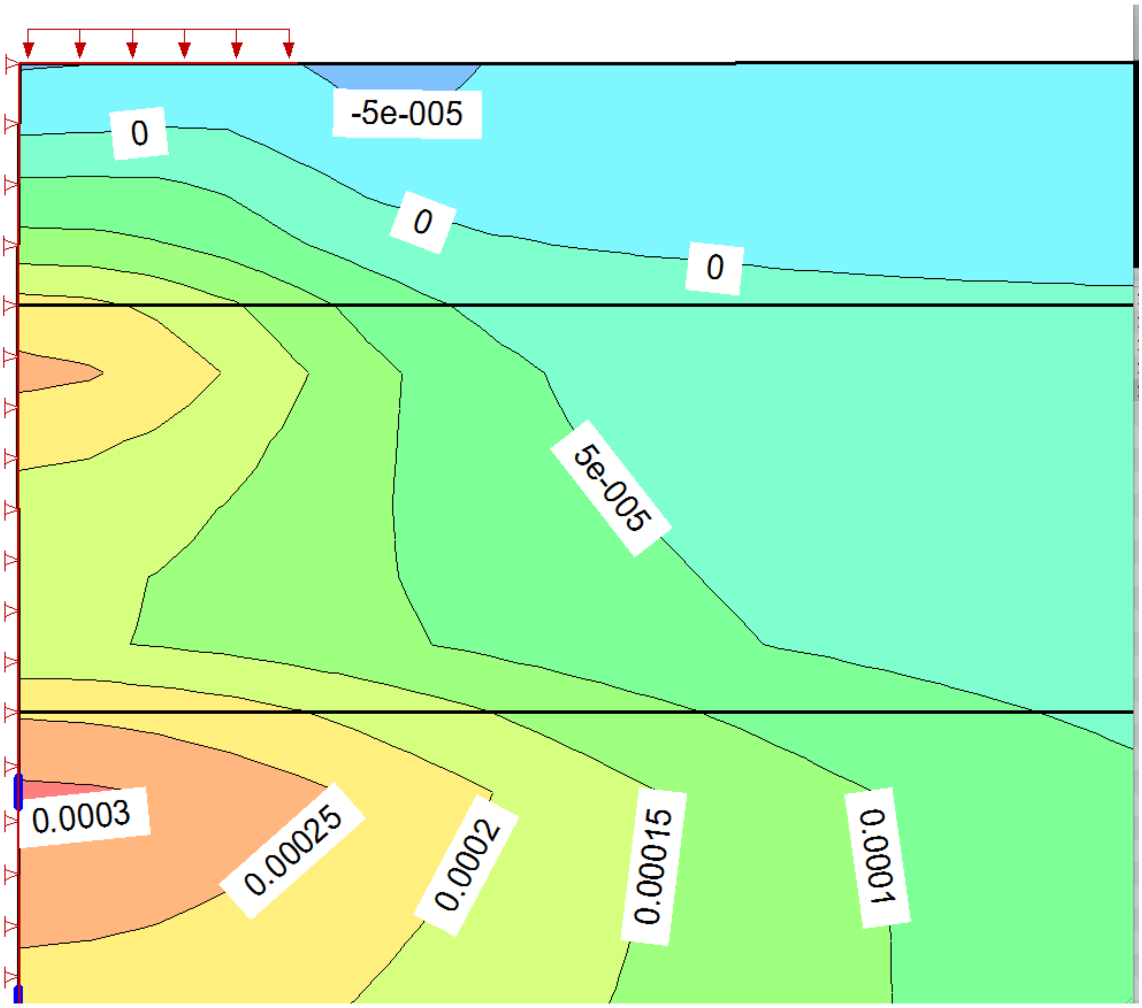
MODEL



VERTICAL DEFLECTIONS

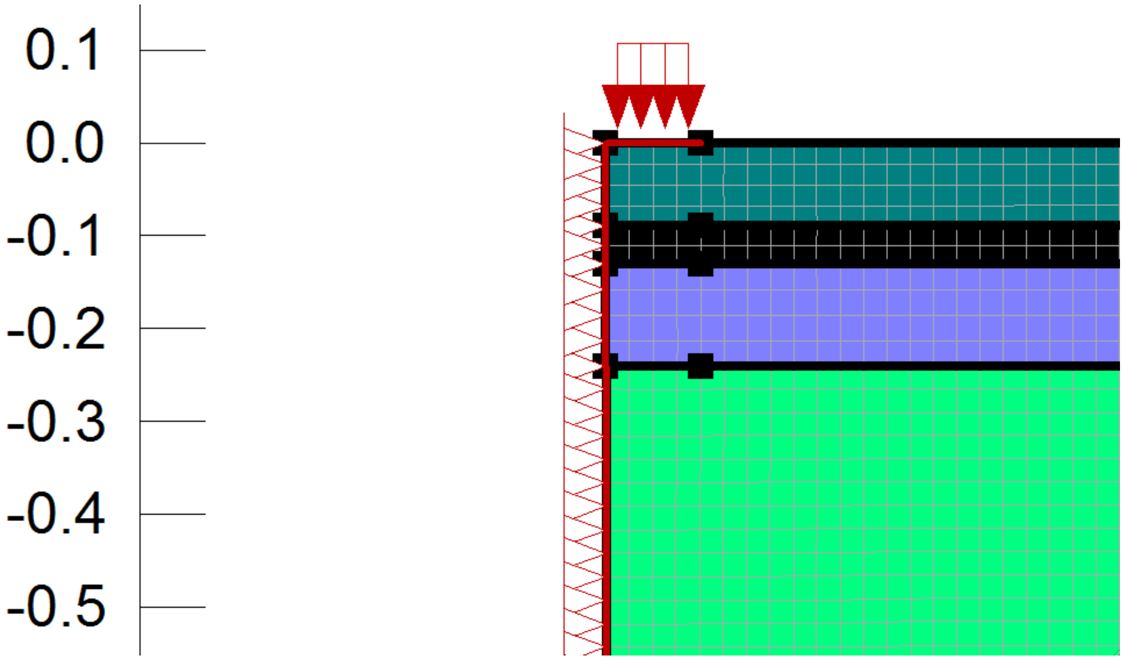


VERTICAL STRAINS

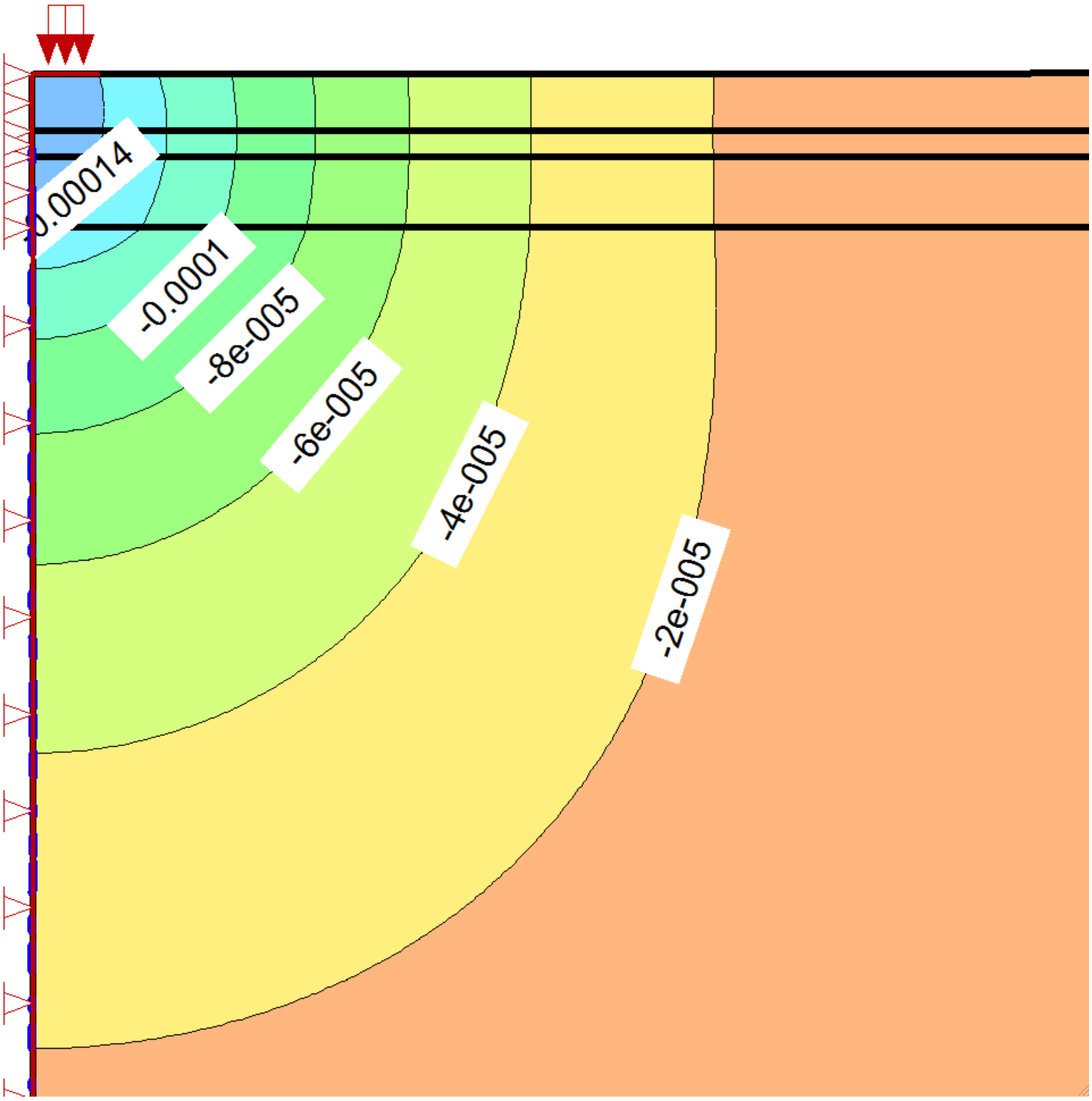


UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
PEDESTRIAN AND DOMESTIC DRIVEWAYS

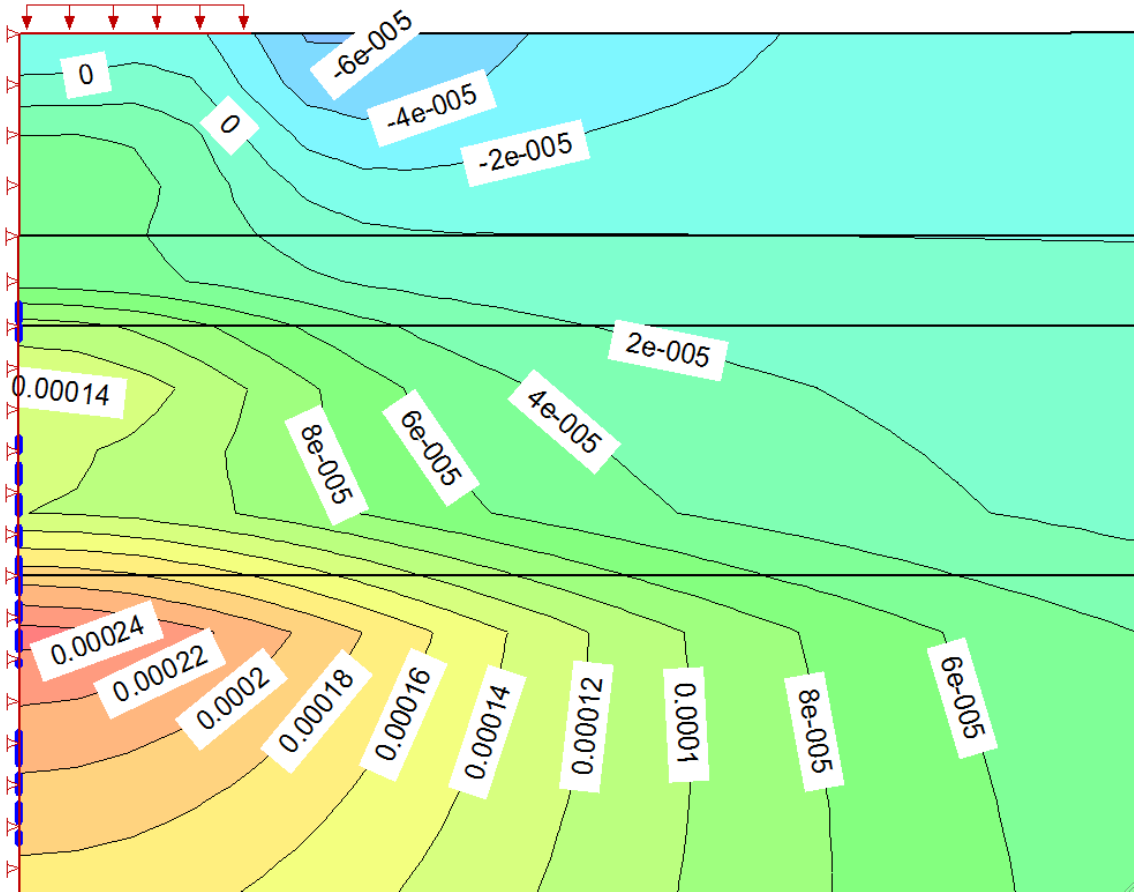
MODEL



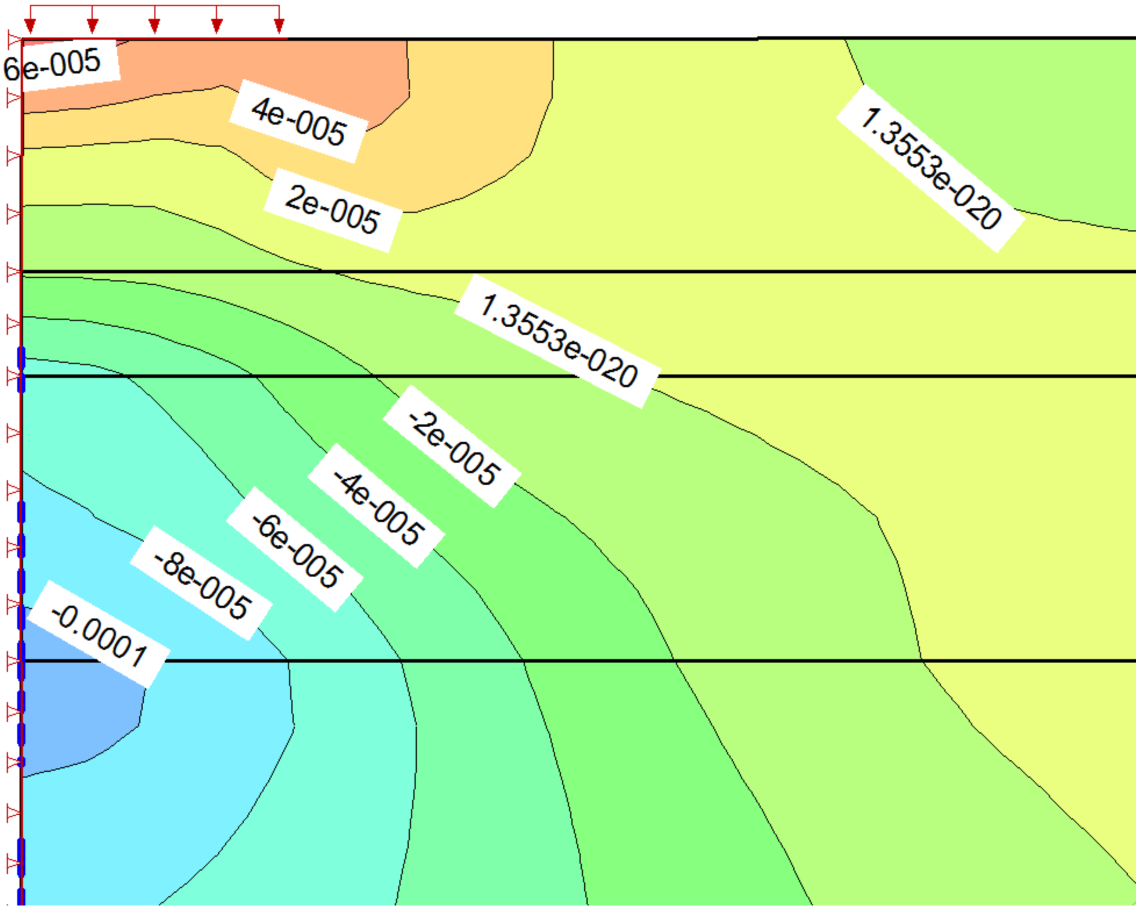
VERTICAL DEFLECTIONS



VERTICAL STRAINS

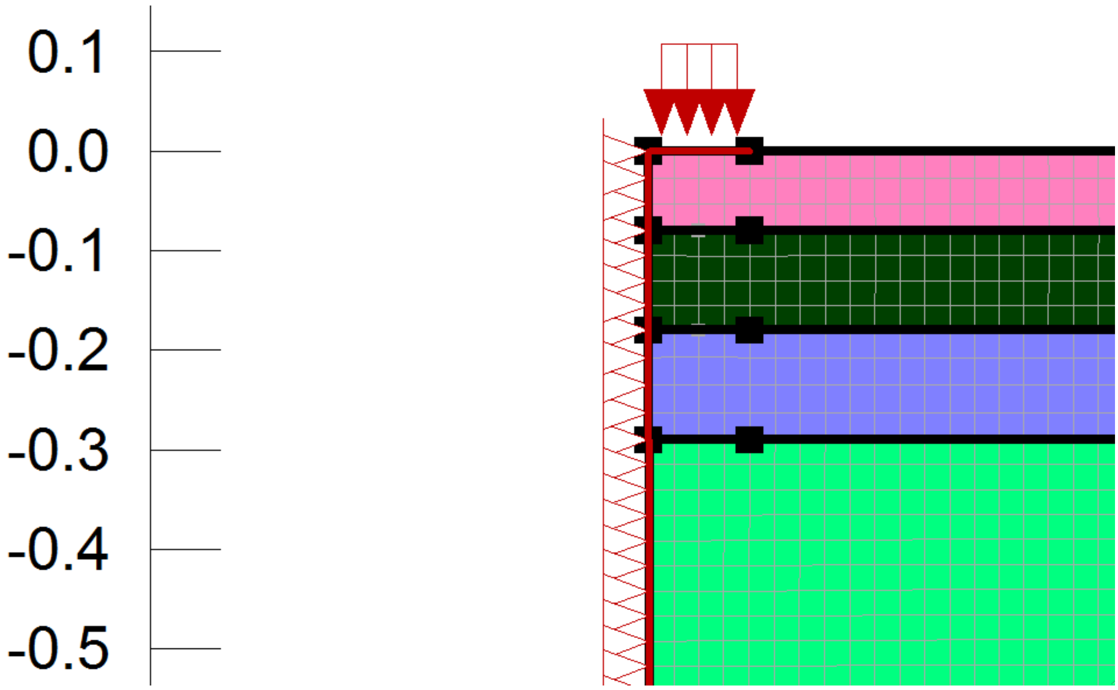


HORIZONTAL STRAINS

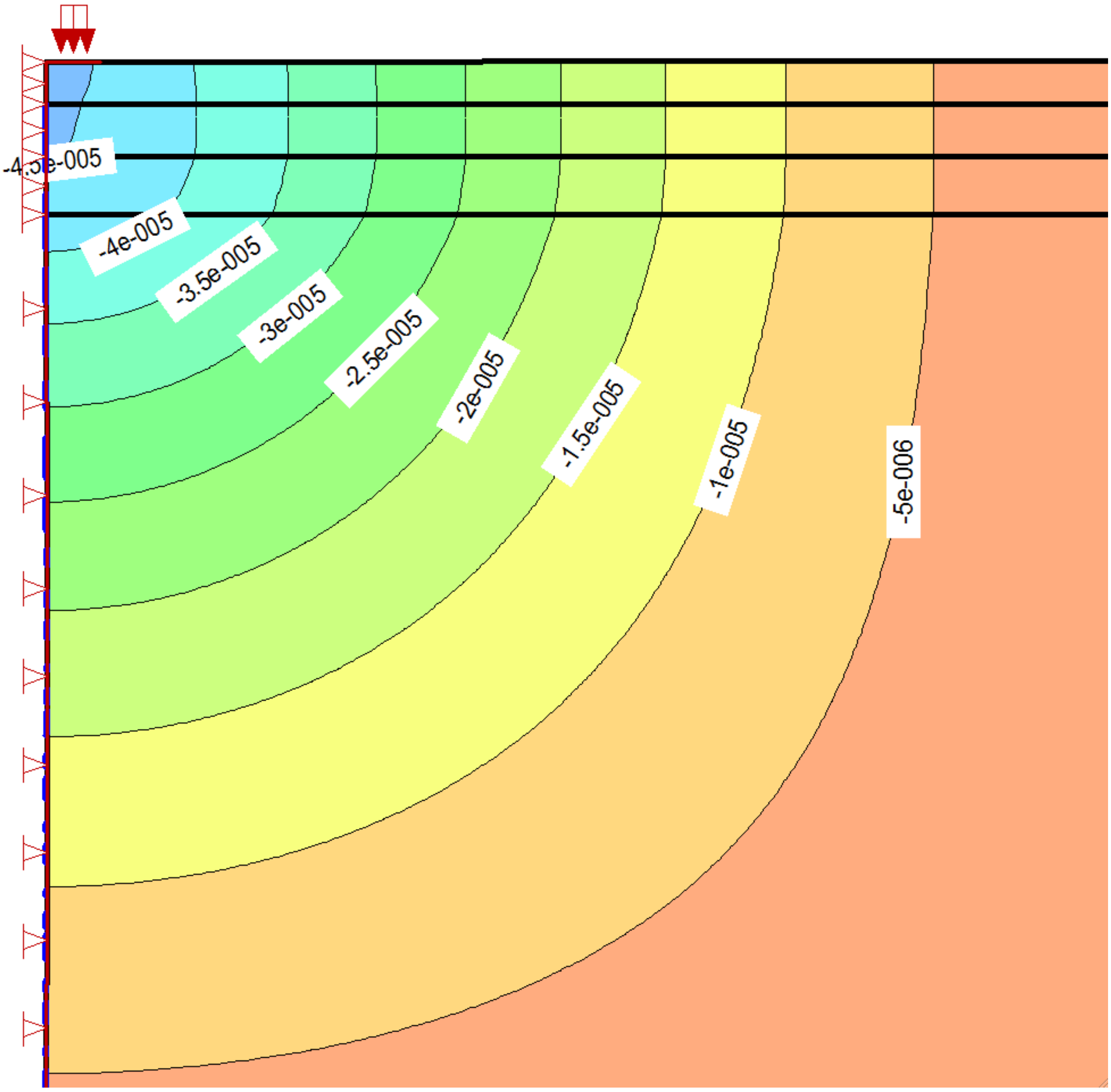


BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
PEDESTRIAN AND DOMESTIC DRIVEWAYS

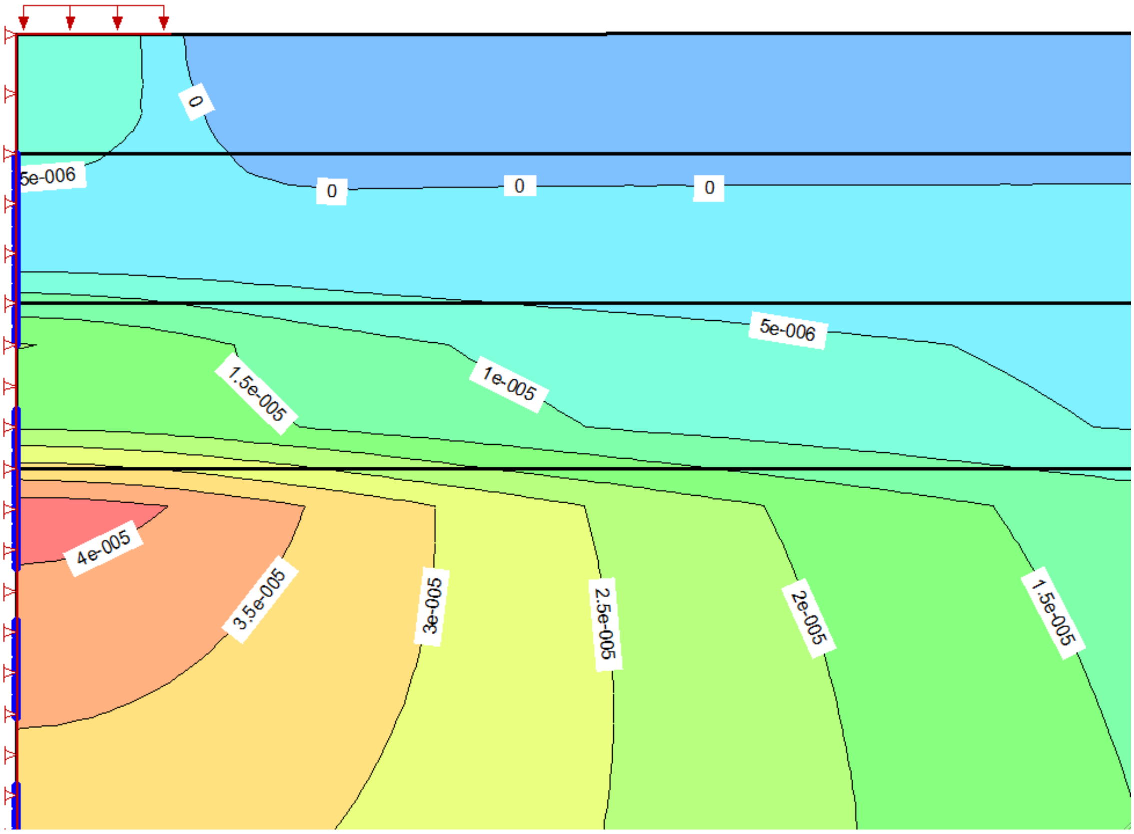
MODEL



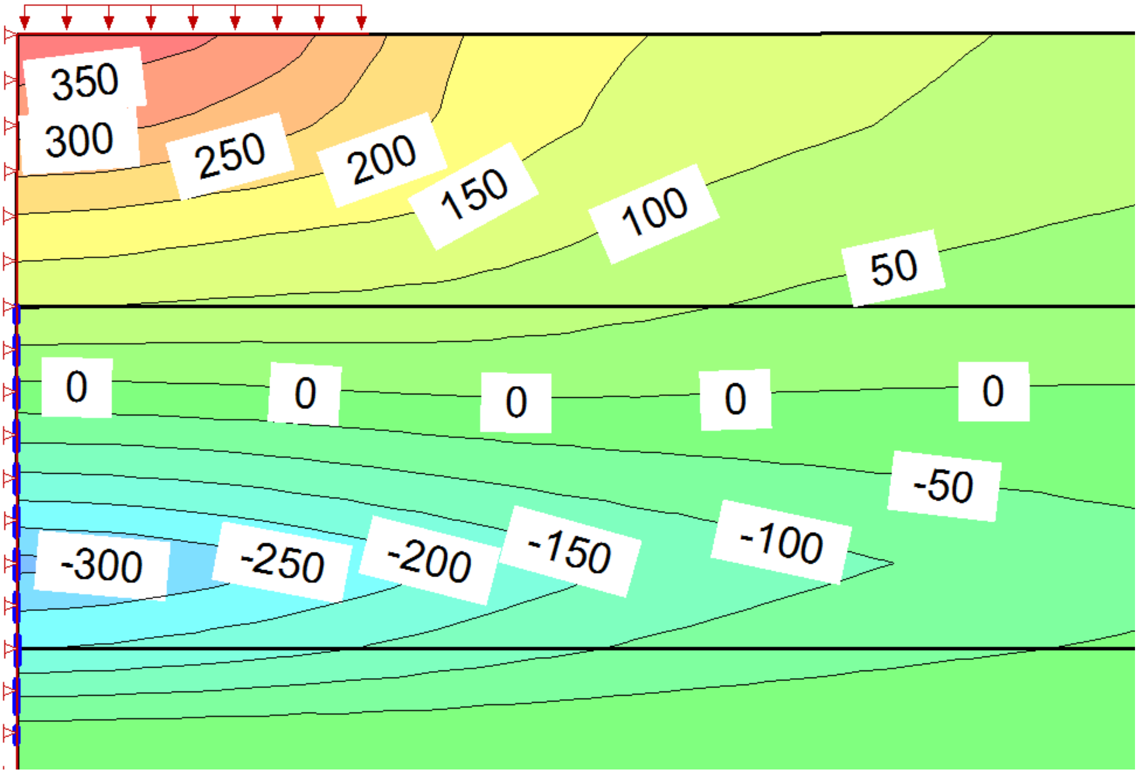
VERTICAL DEFLECTIONS



VERTICAL STRAINS

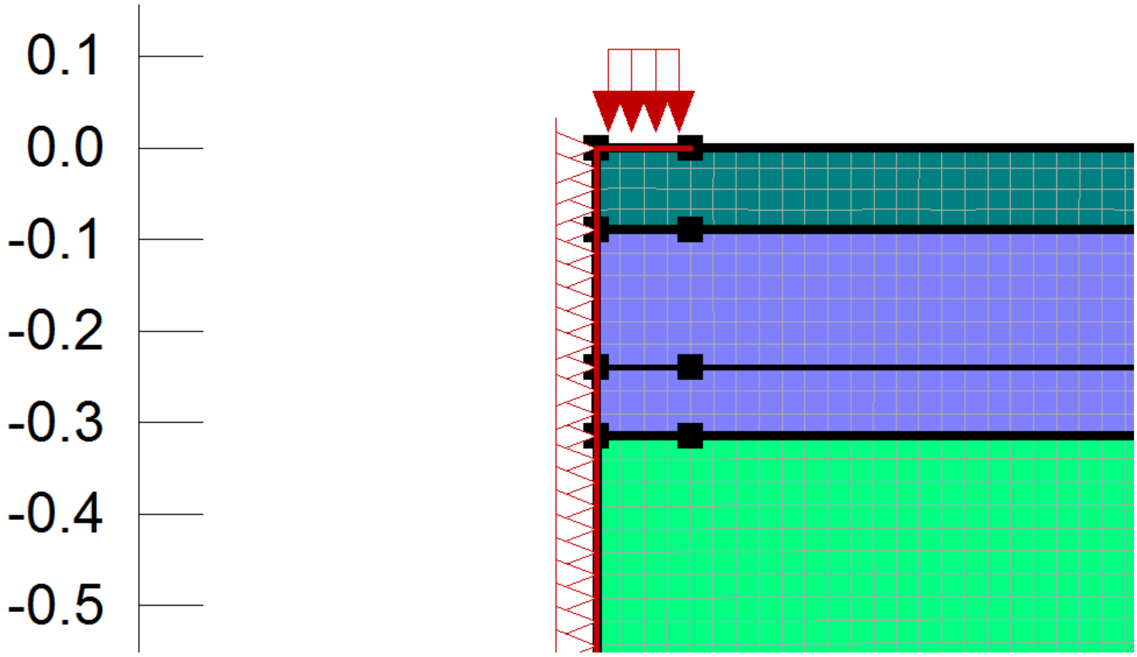


HORIZONTAL STRESSES

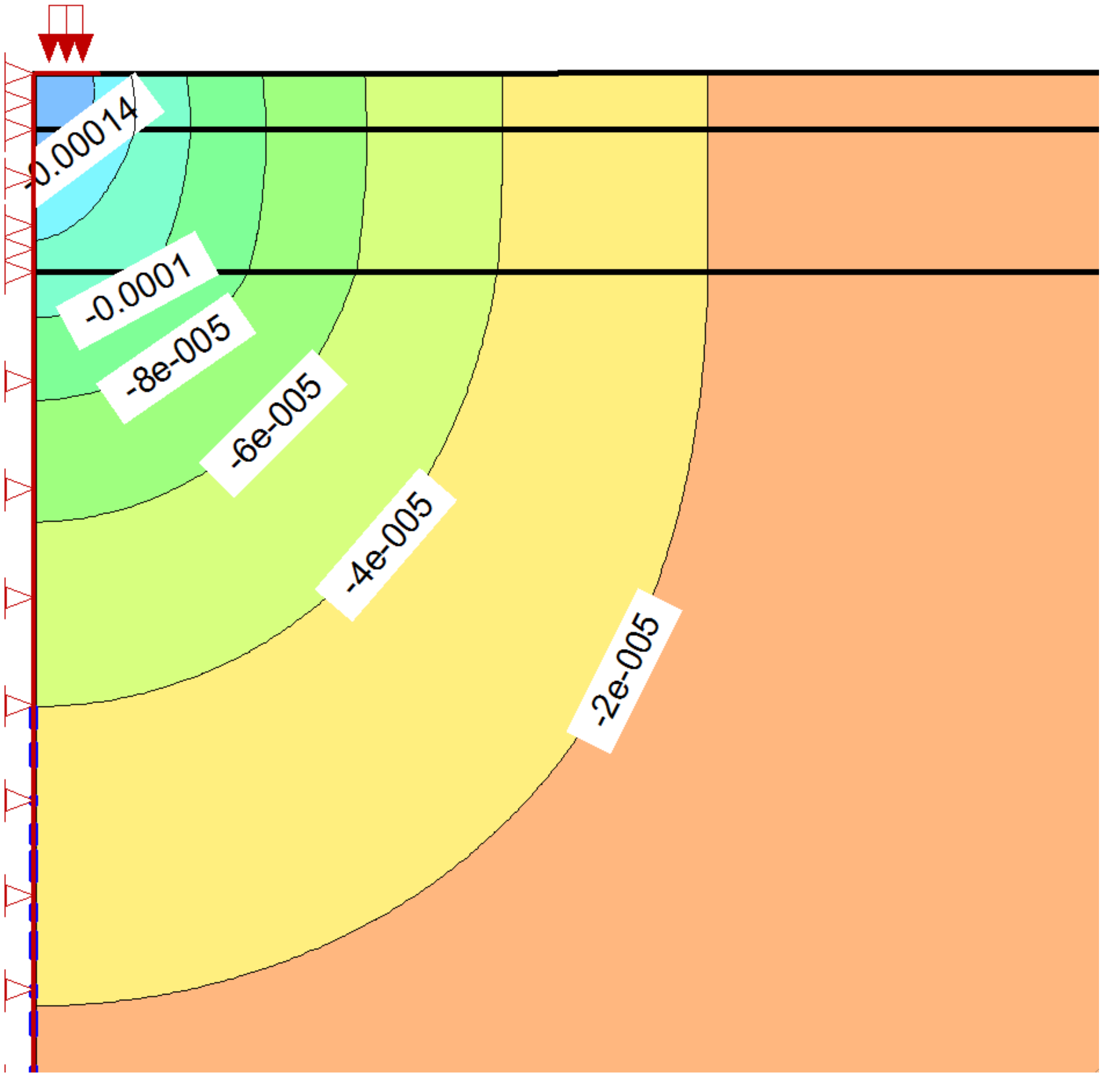


UNBOUND SURFACE UNBOUND BASE
PIETRA PAVE PAVEMENTS
CARS AND LIGHT VANS

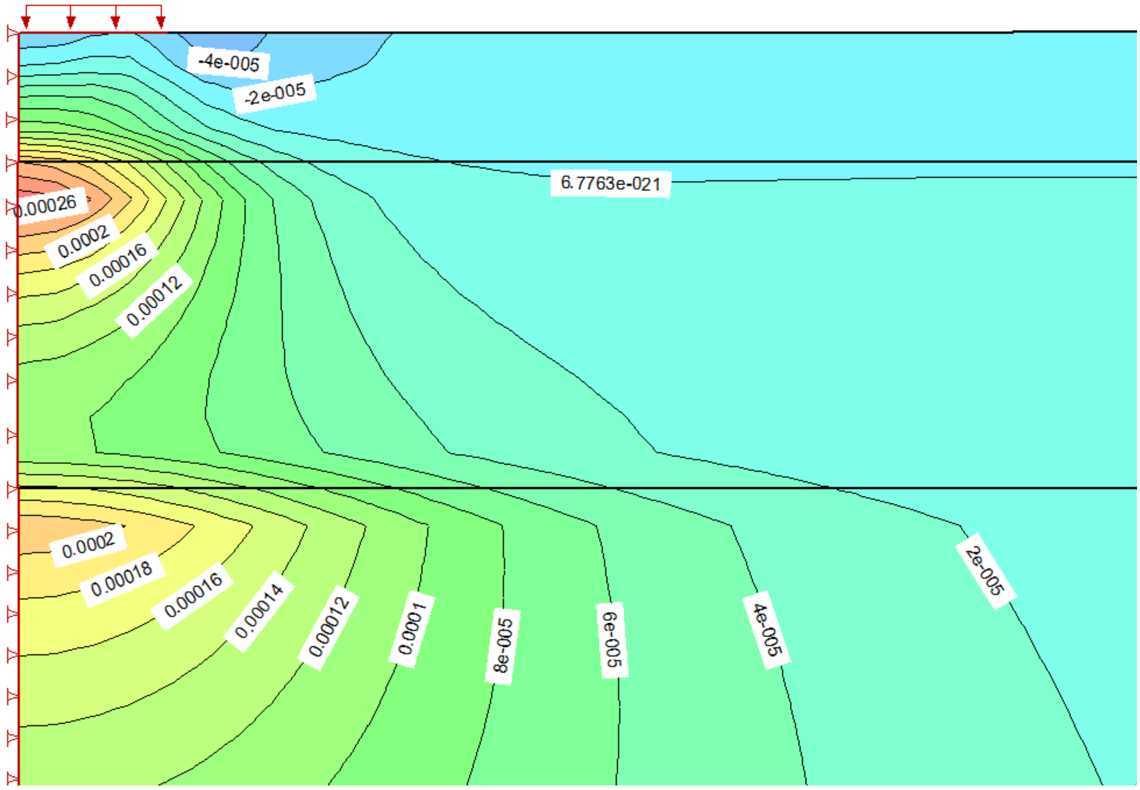
MODEL



VERTICAL DEFLECTIONS

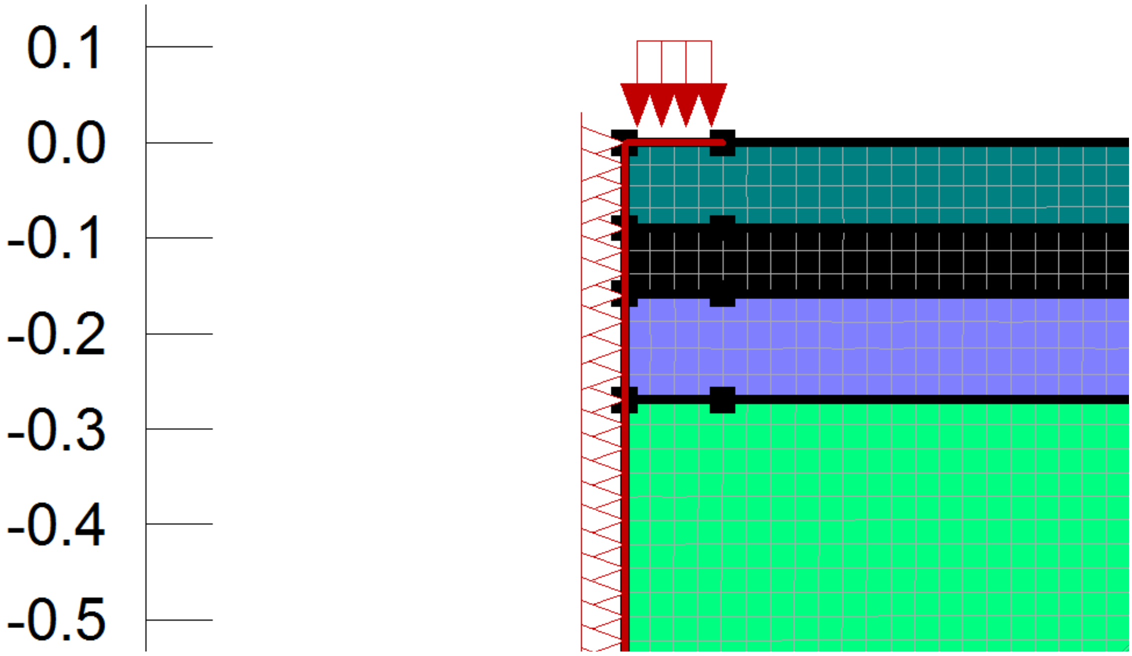


VERTICAL STRAINS



UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
CARS AND LIGHT VANS

MODEL



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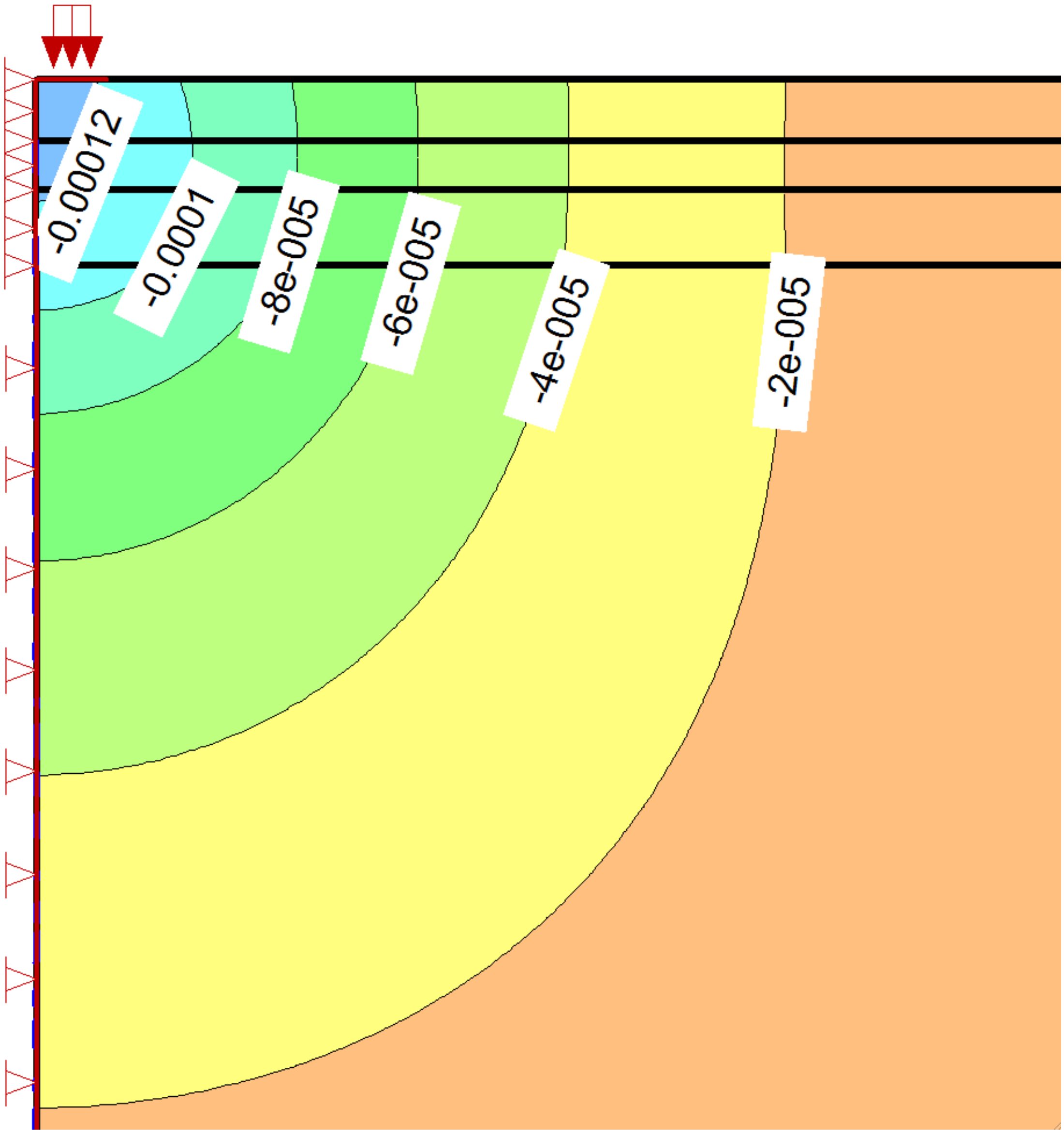

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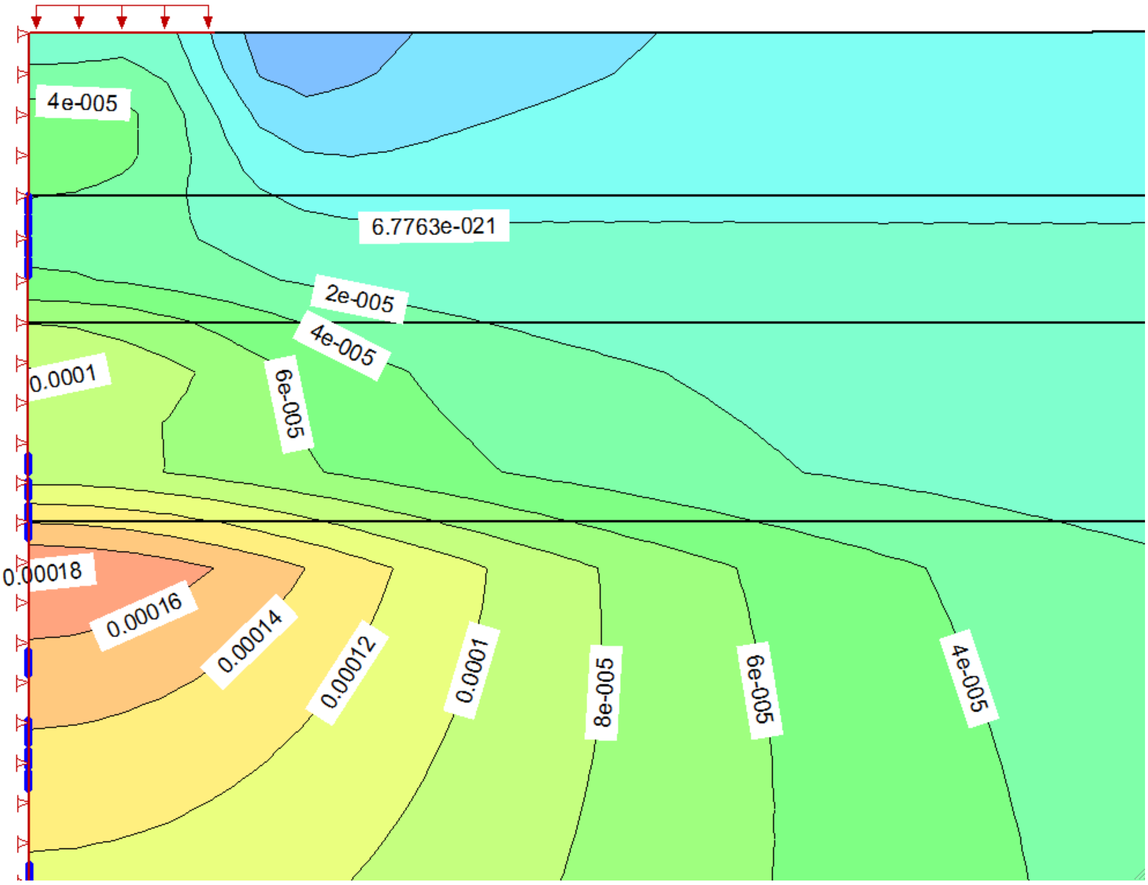

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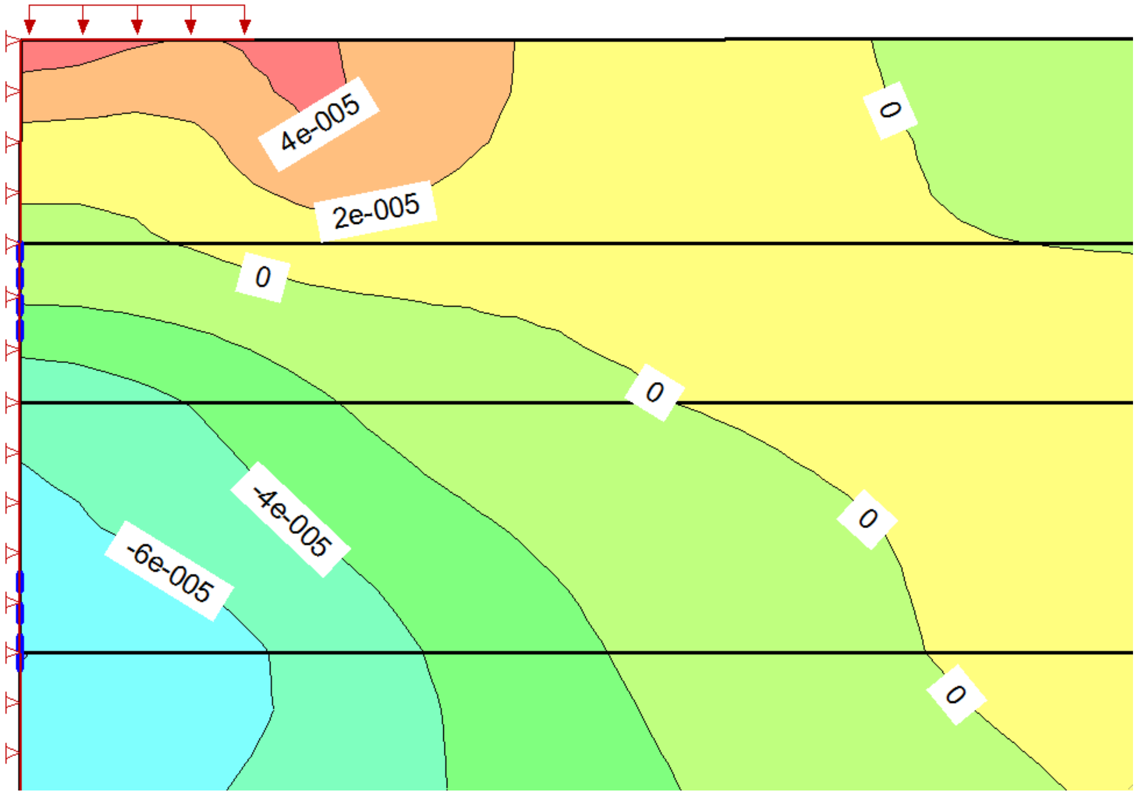
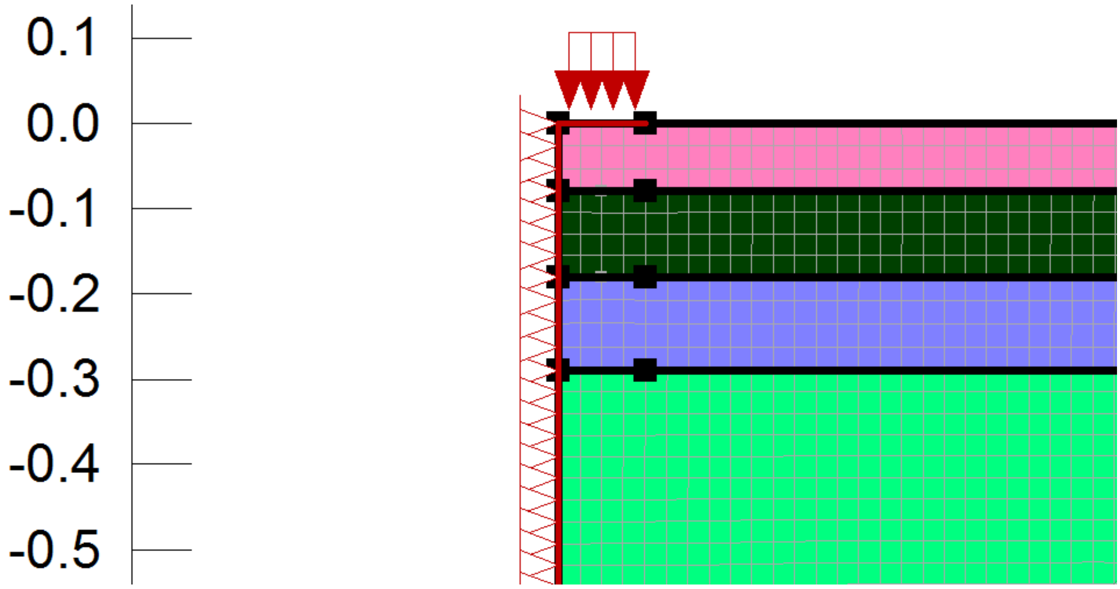


BOUND SURFACE RIGID BASE PIETRA PAVE PAVEMENTS CARS AND LIGHT VANS

MODEL



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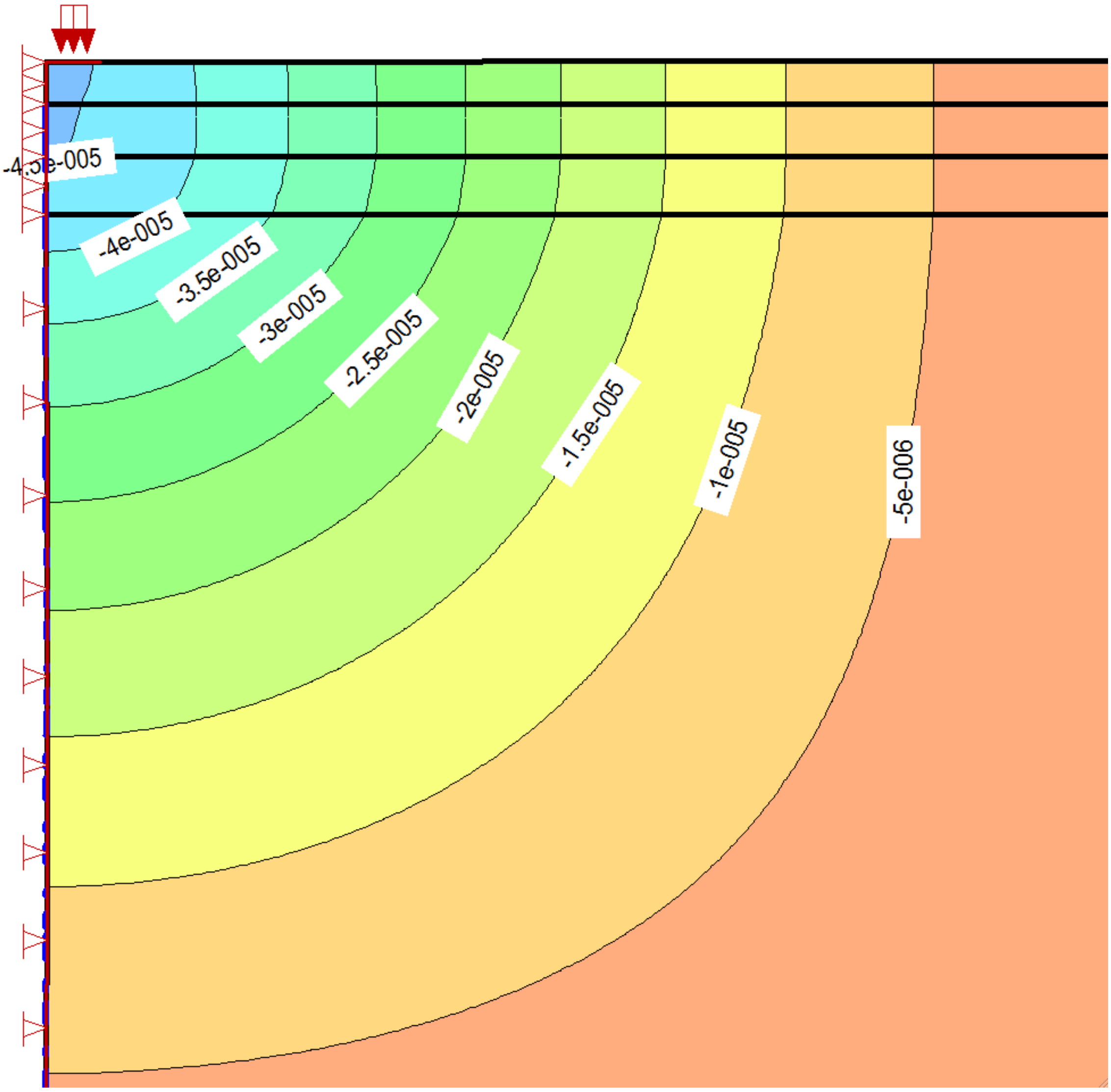

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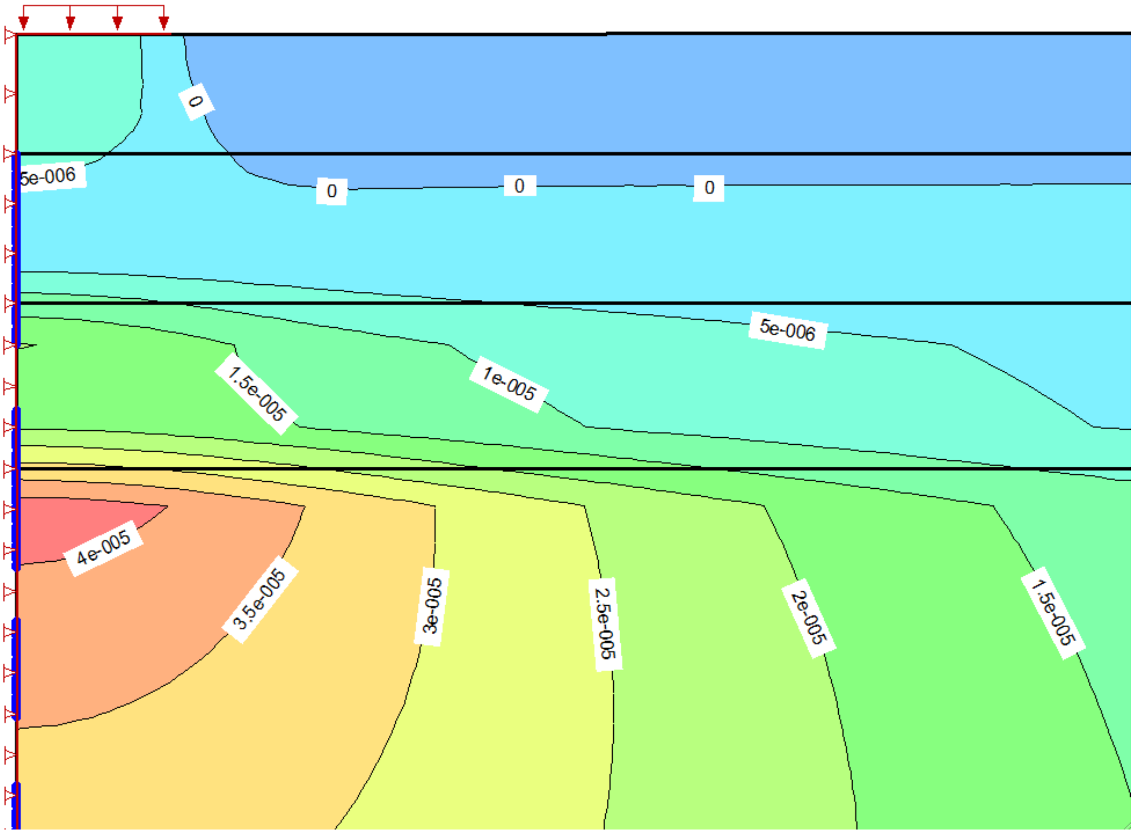
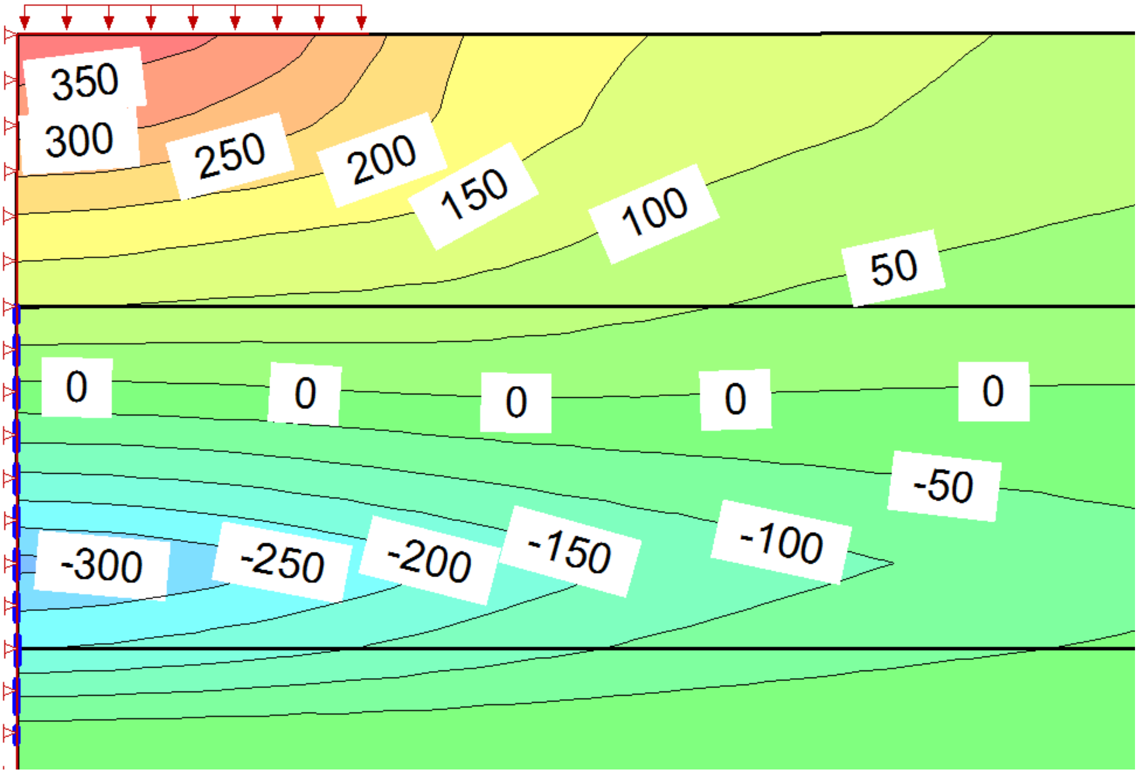
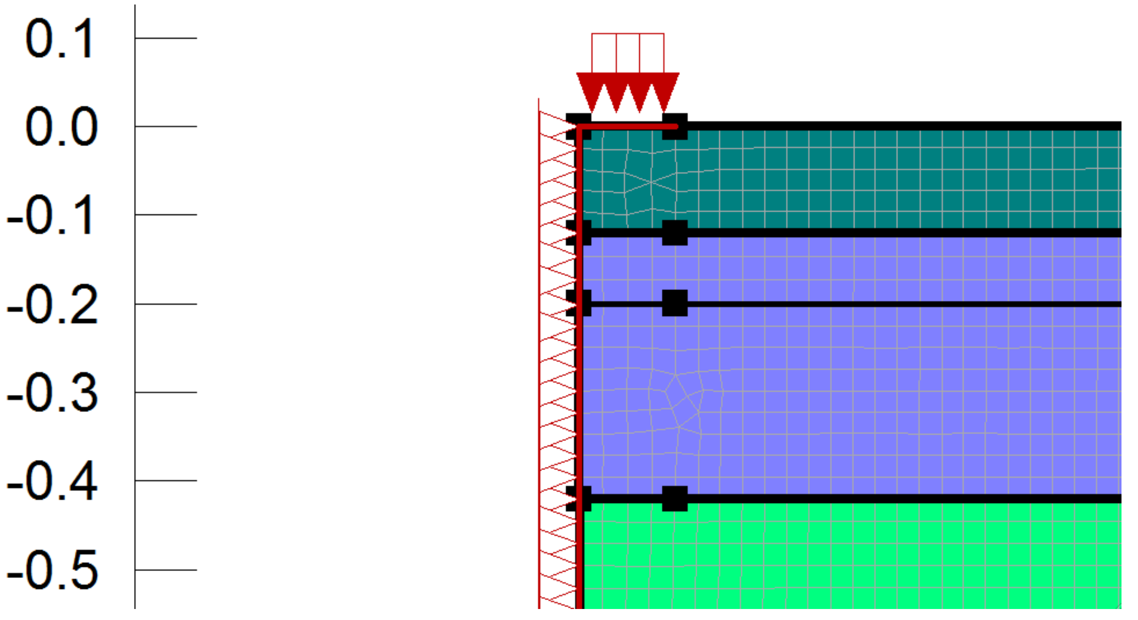


HORIZONTAL STRESSES

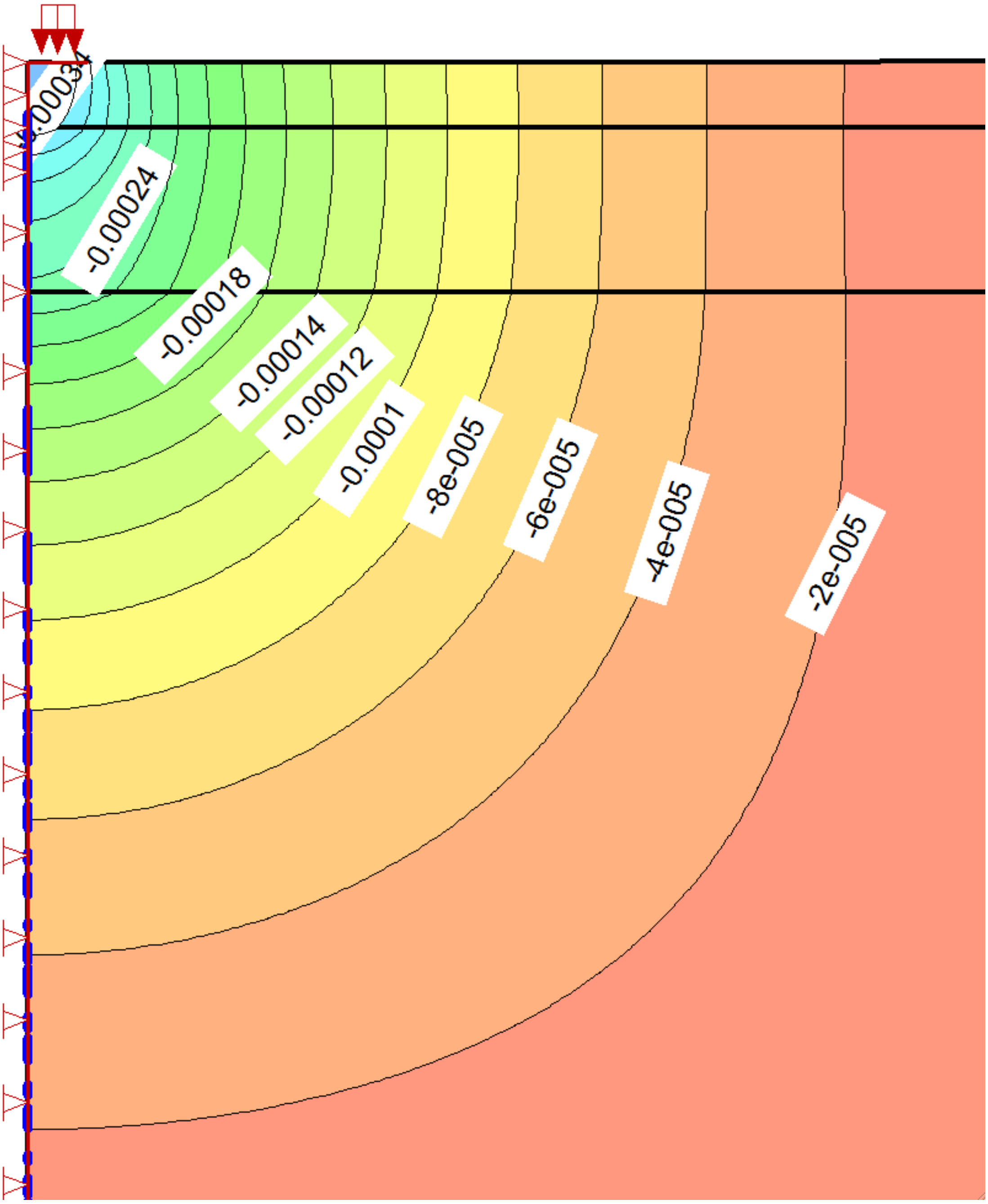


UNBOUND SURFACE UNBOUND BASE PIETRA PAVE PAVEMENTS TRAFFIC UP TO 7.5TONNE

MODEL



VERTICAL DEFLECTIONS



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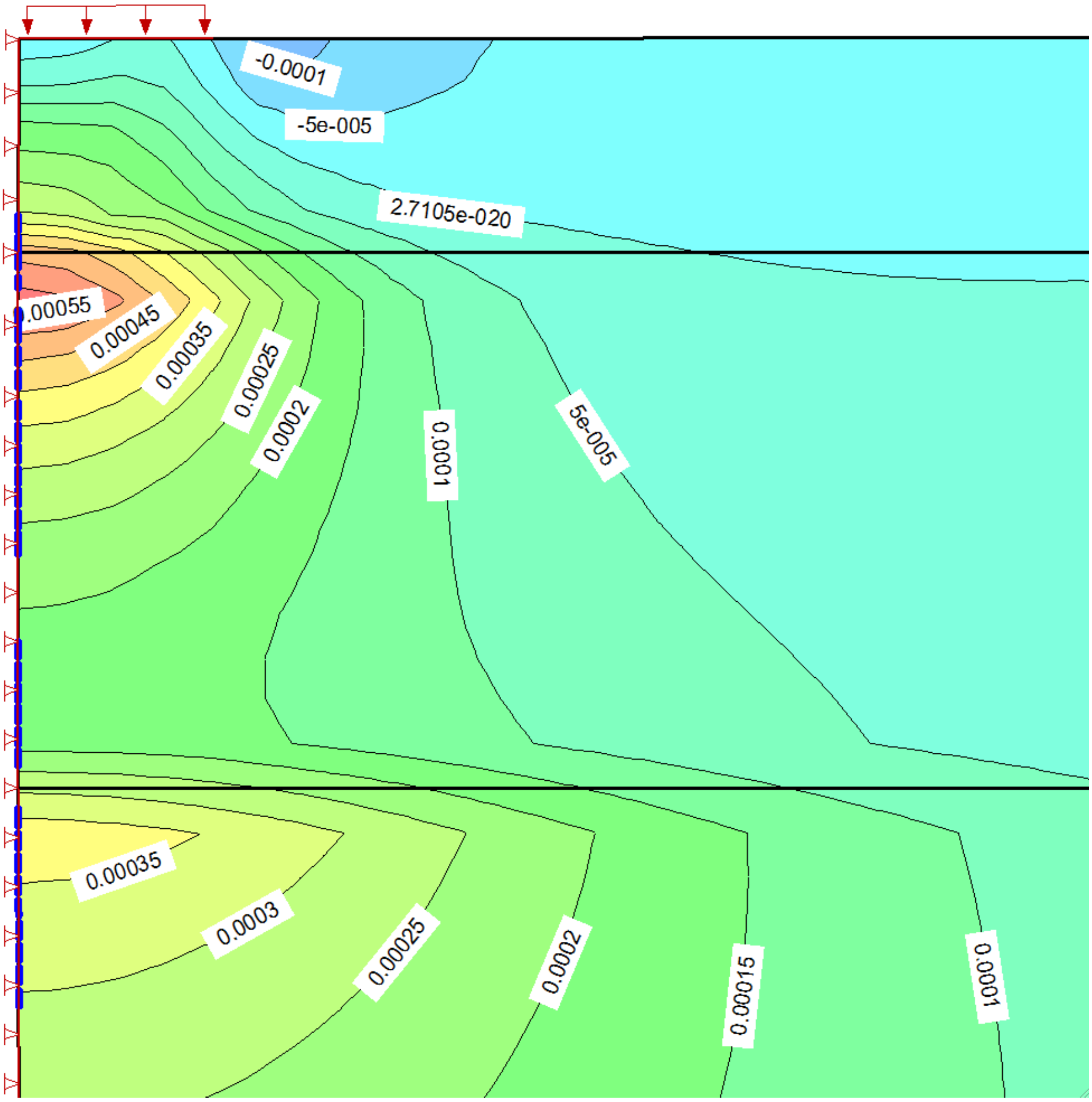
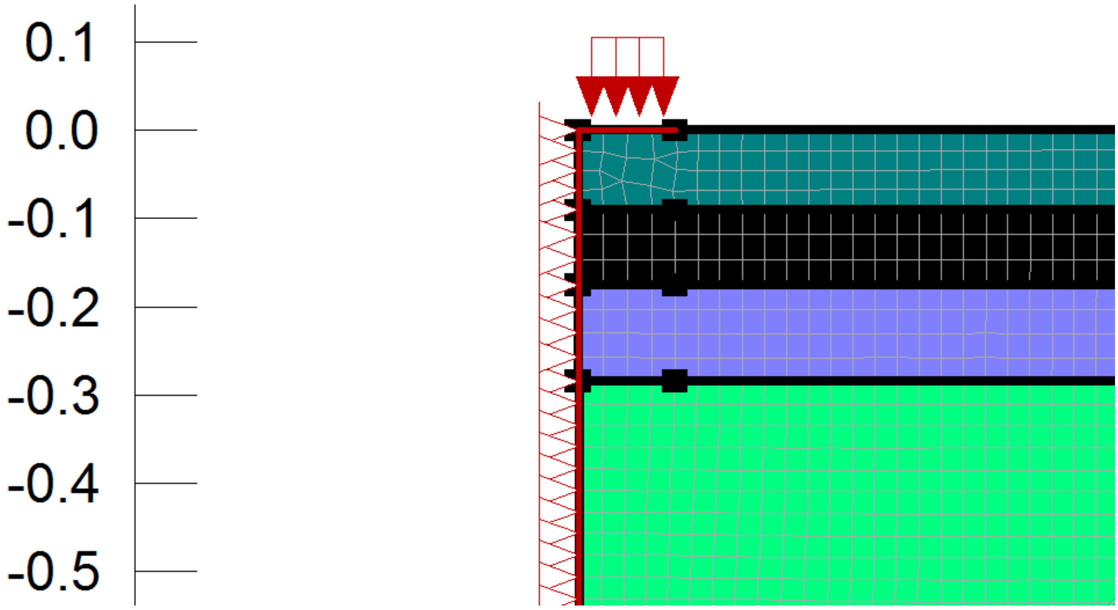


UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
TRAFFIC UP TO 7.5TONNE

MODEL



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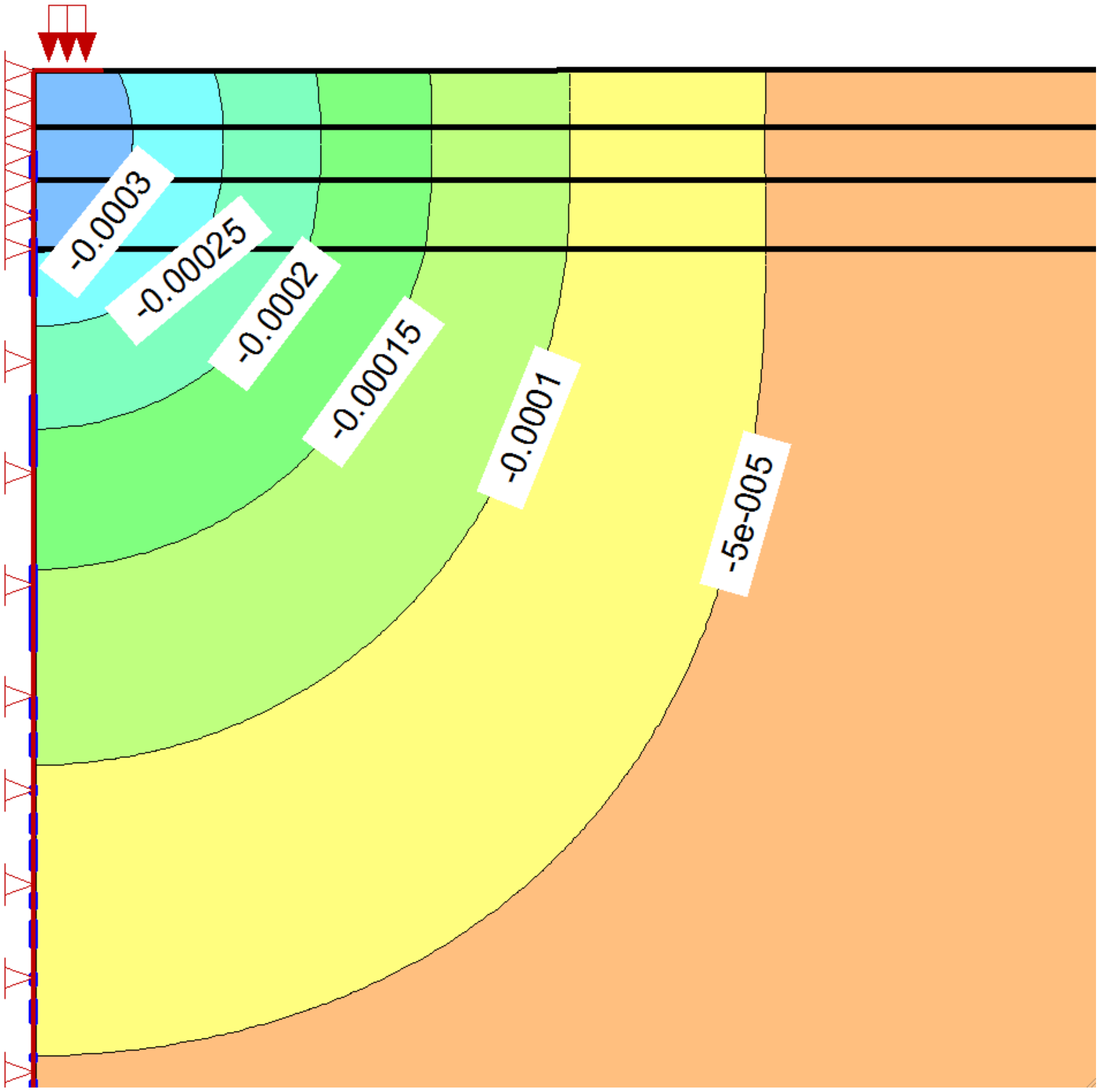

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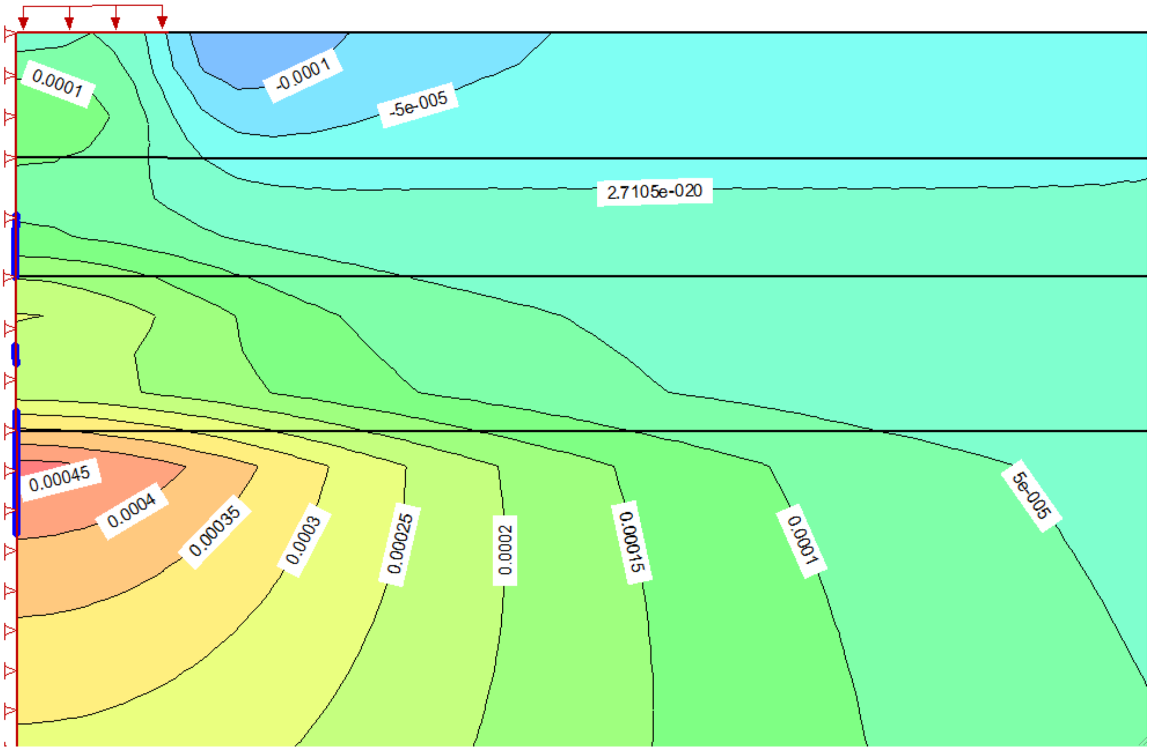
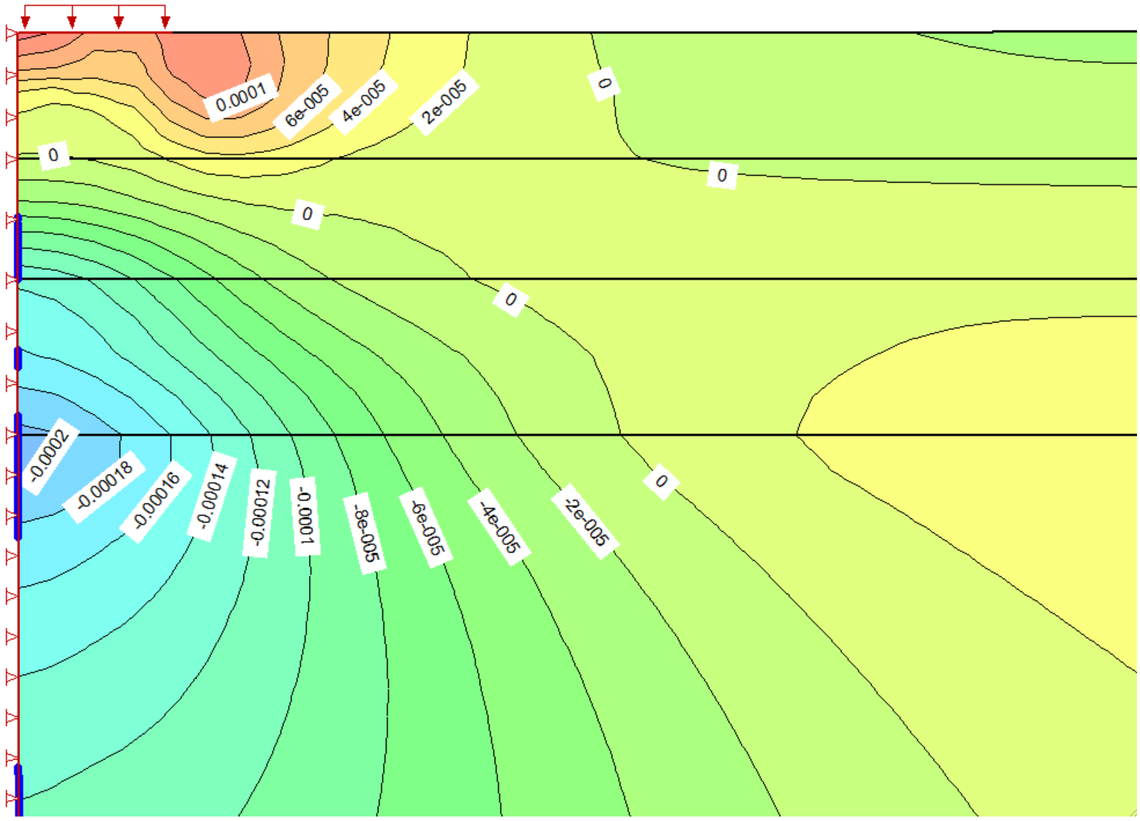
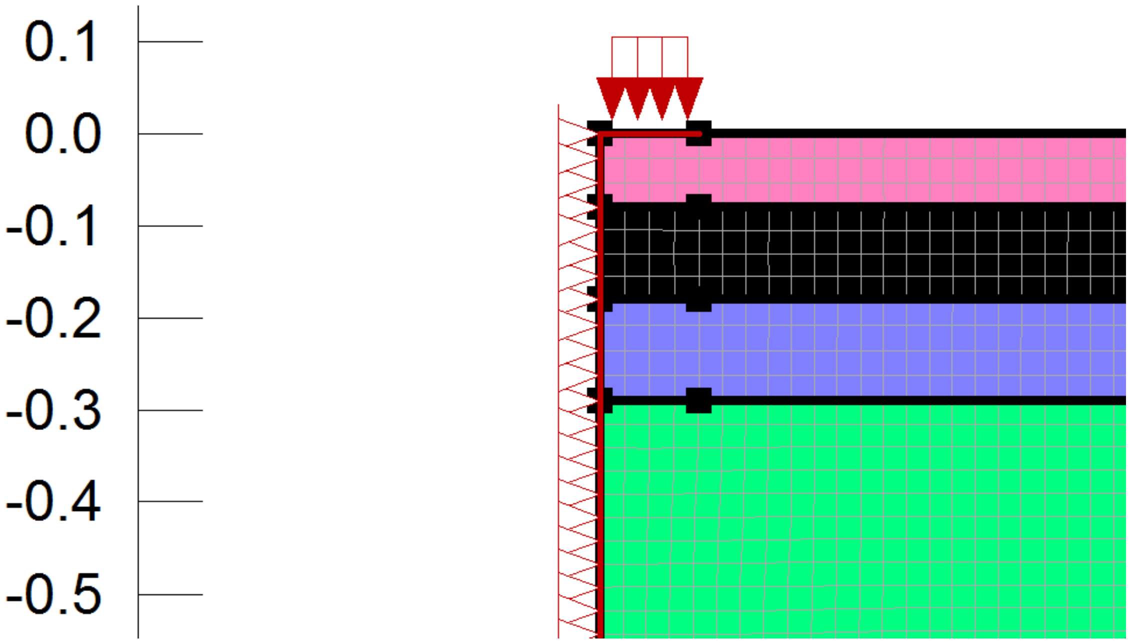


HORIZONTAL STRAINS



BOUND SURFACE RIGID BASE PIETRA PAVE PAVEMENTS TRAFFIC UP TO 7.5TONNE

MODEL



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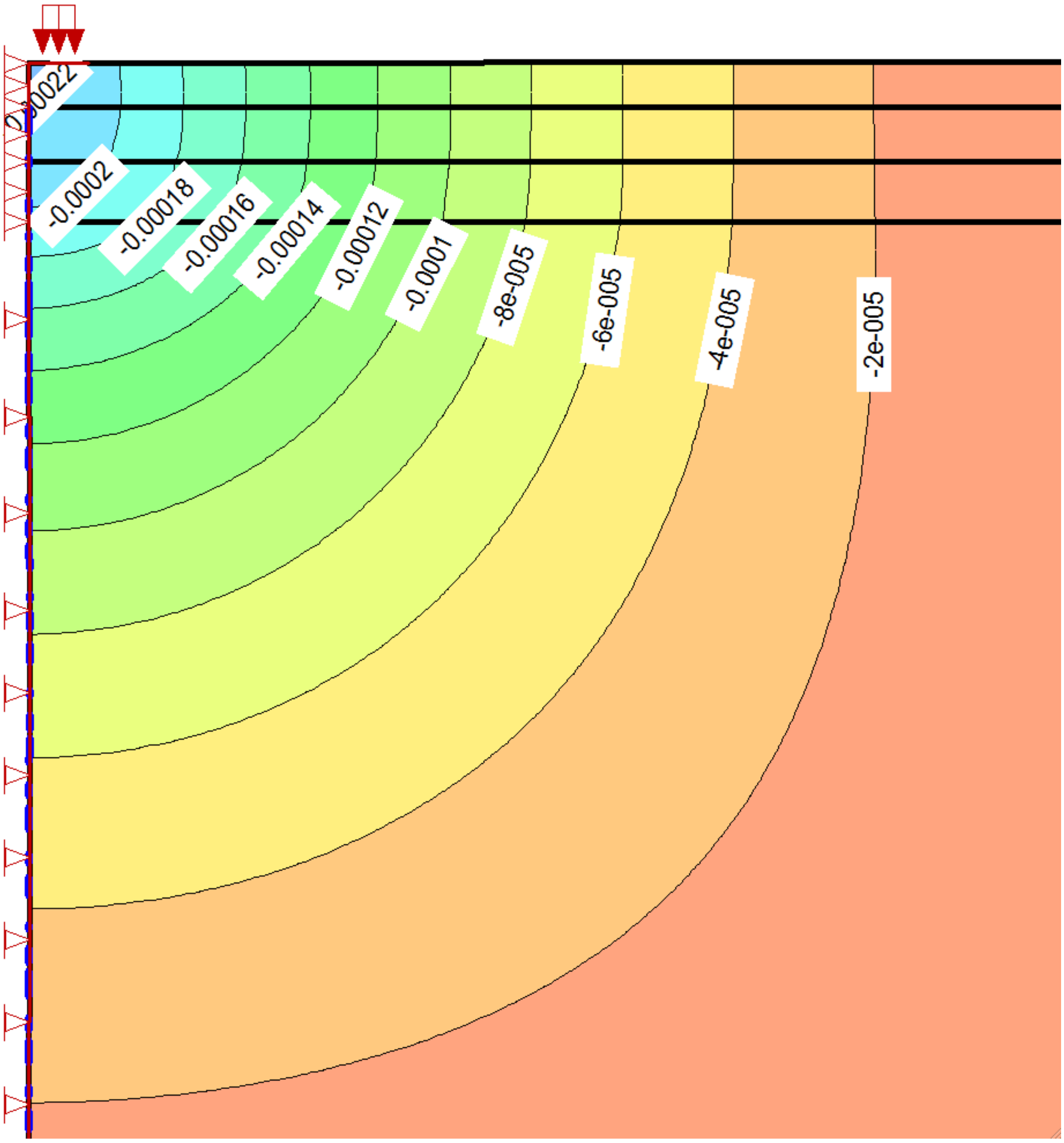
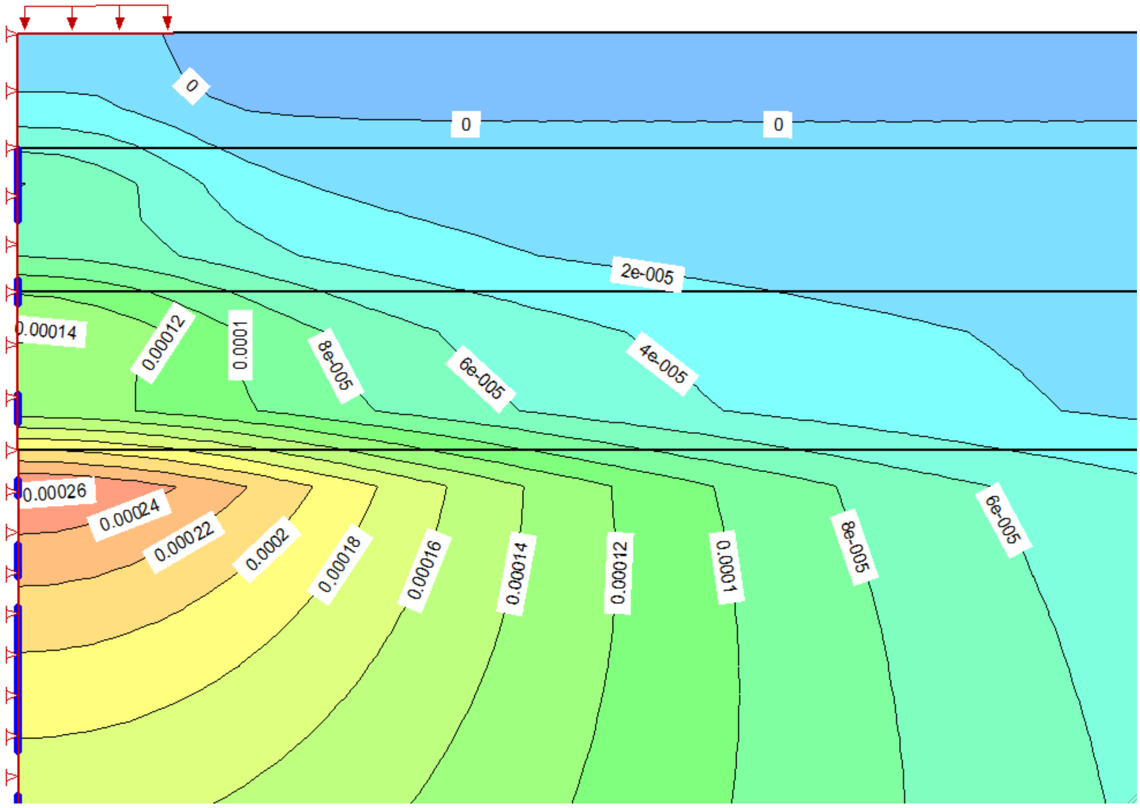
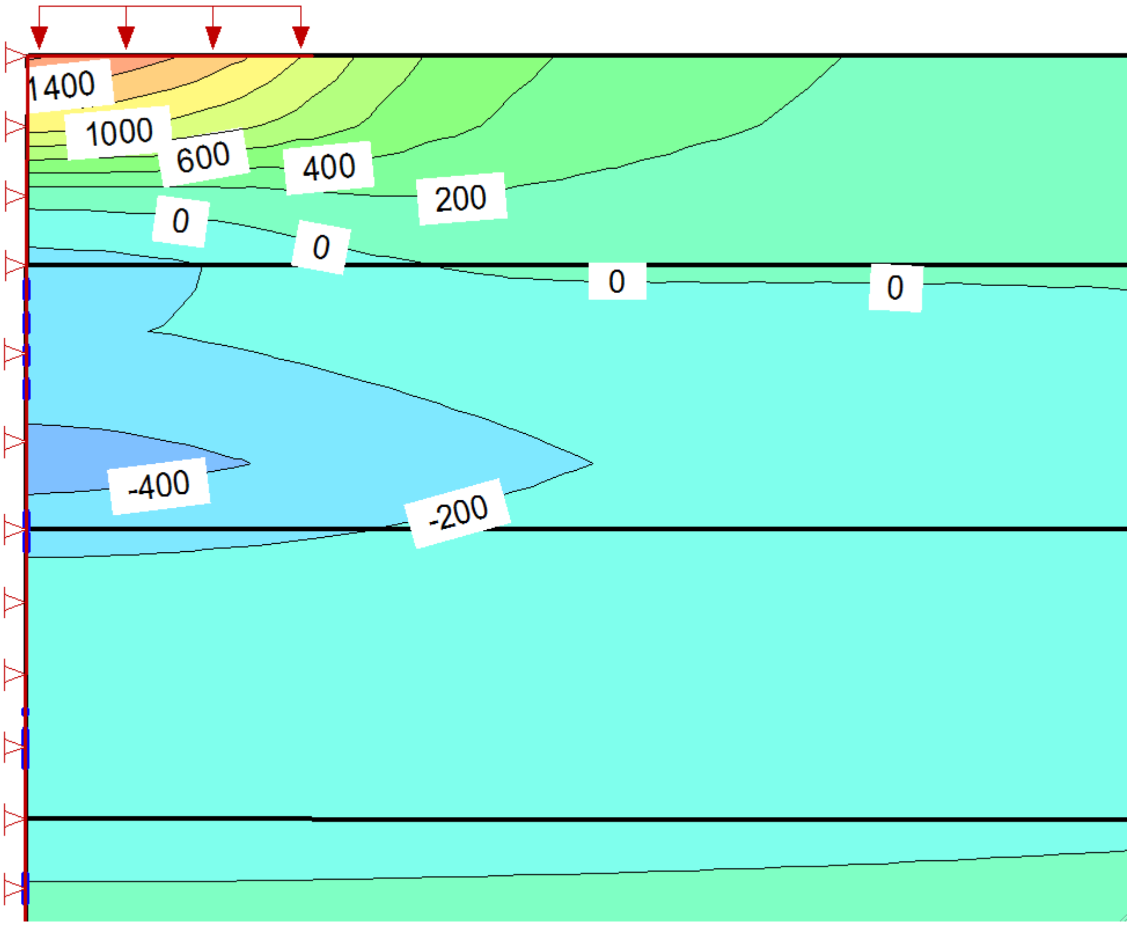


VERTICAL STRAINS

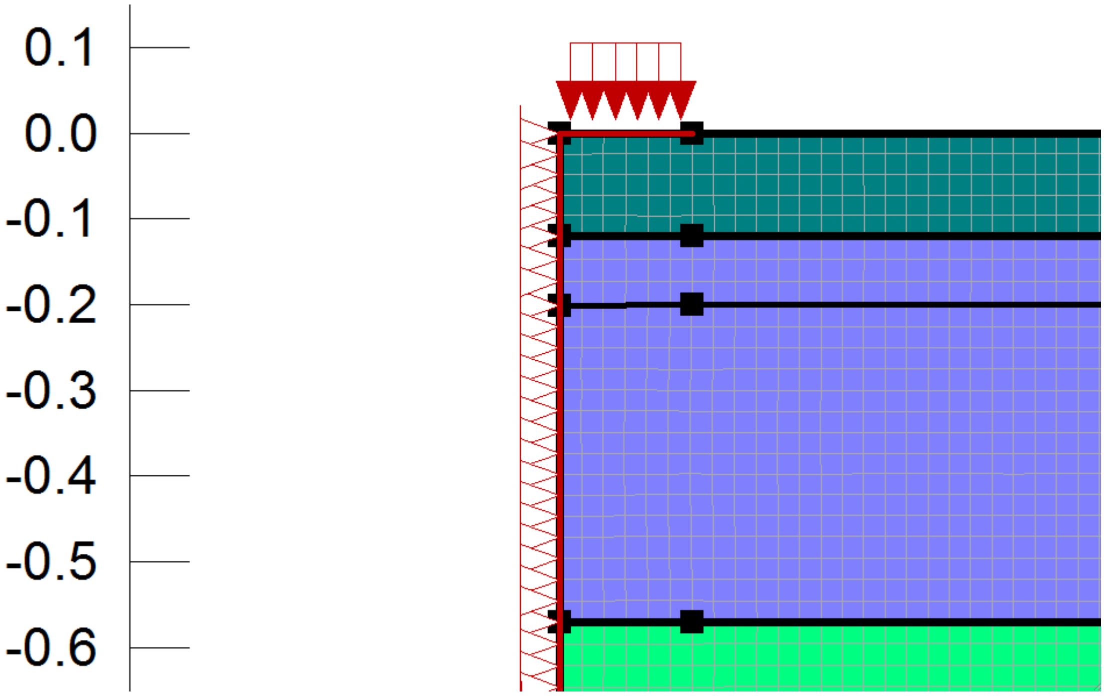


HORIZONTAL STRESSES

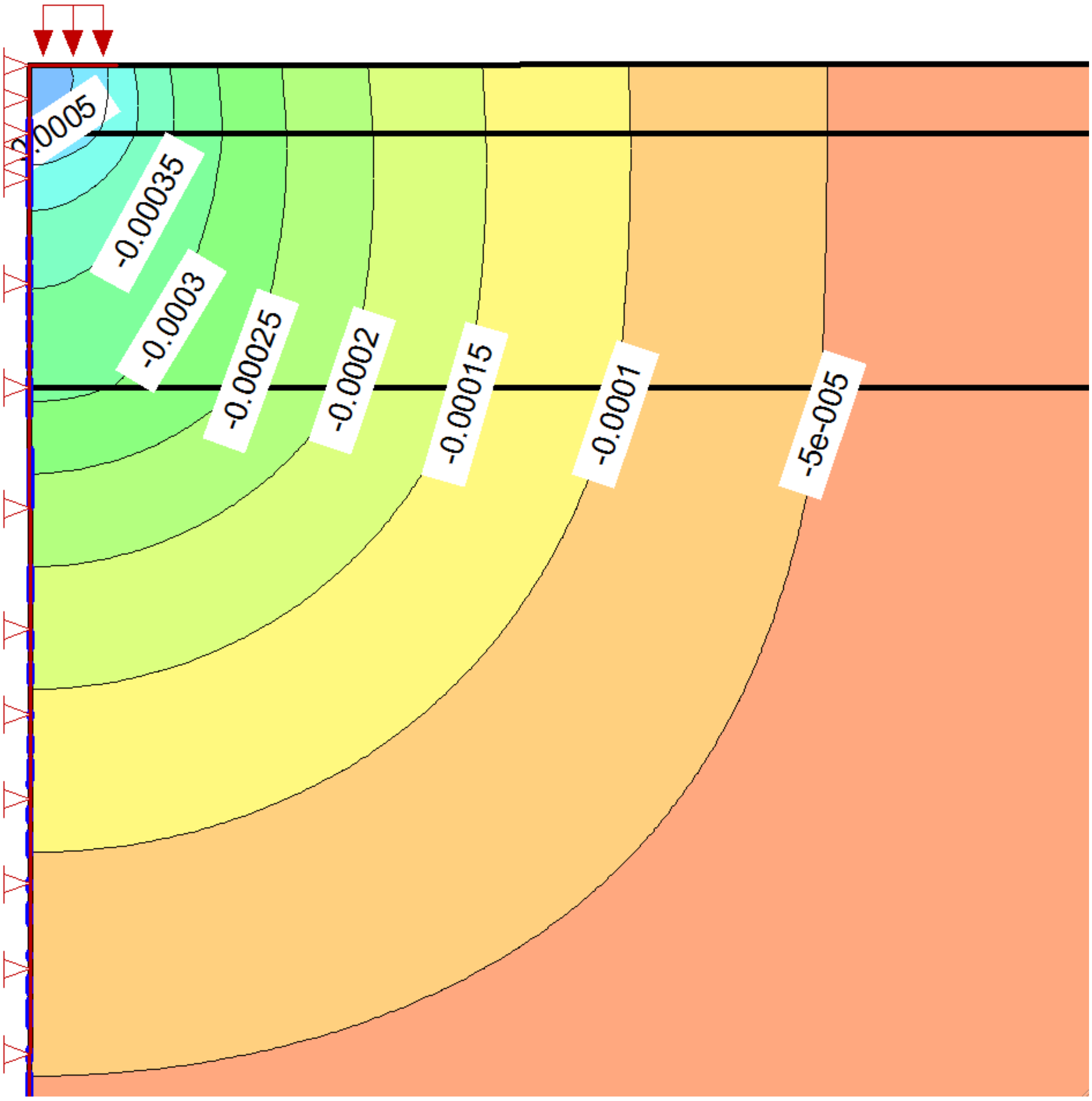


UNBOUND SURFACE UNBOUND BASE
PIETRA PAVE PAVEMENTS
EMERGENCY LARGE GOODS VEHICLES ONLY

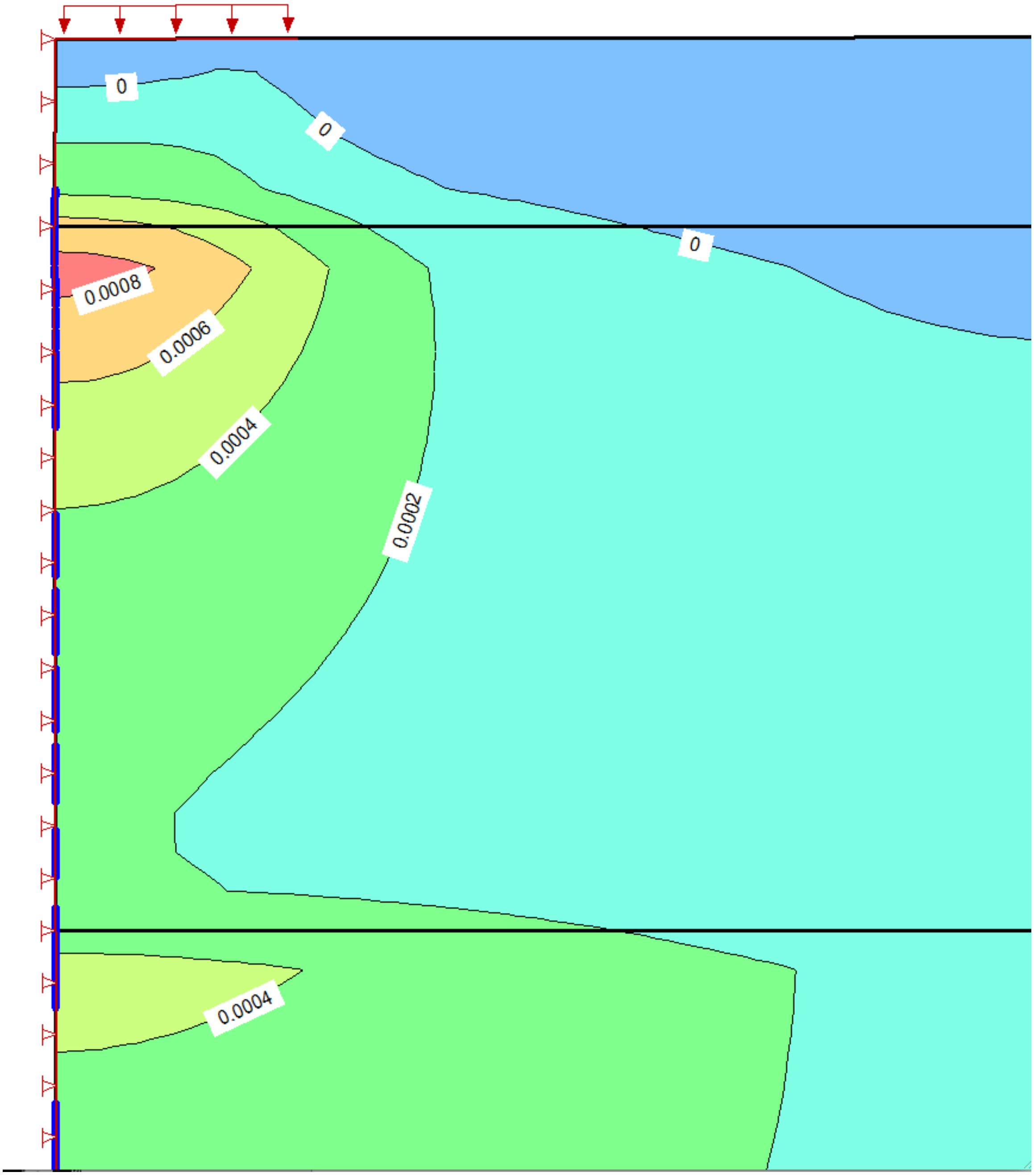
MODEL



VERTICAL DEFLECTIONS

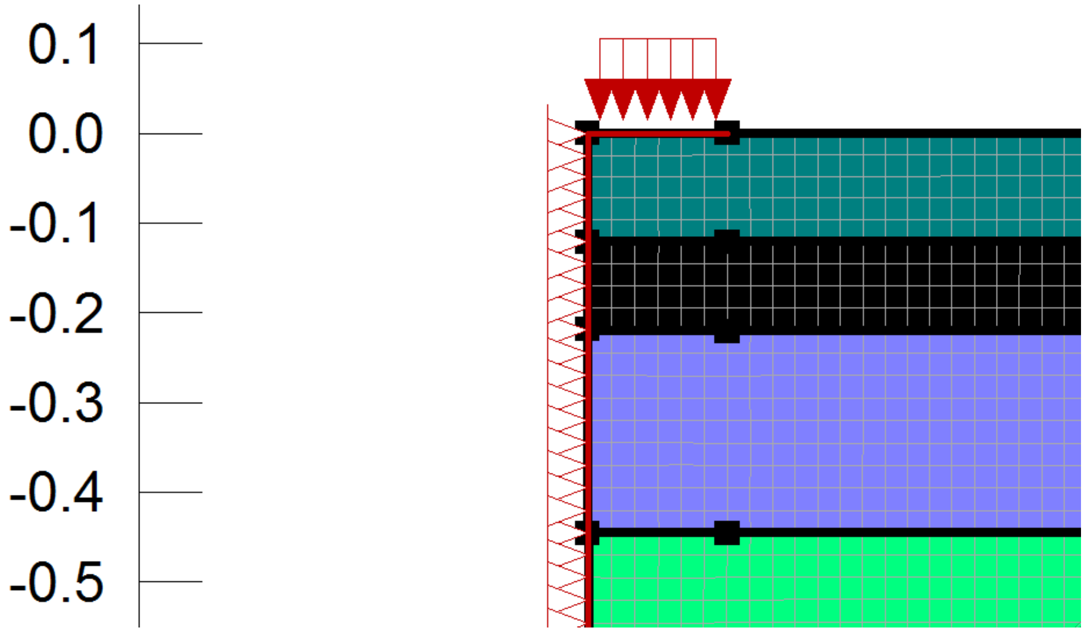


VERTICAL STRAINS



UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
EMERGENCY LARGE GOODS VEHICLES ONLY

MODEL



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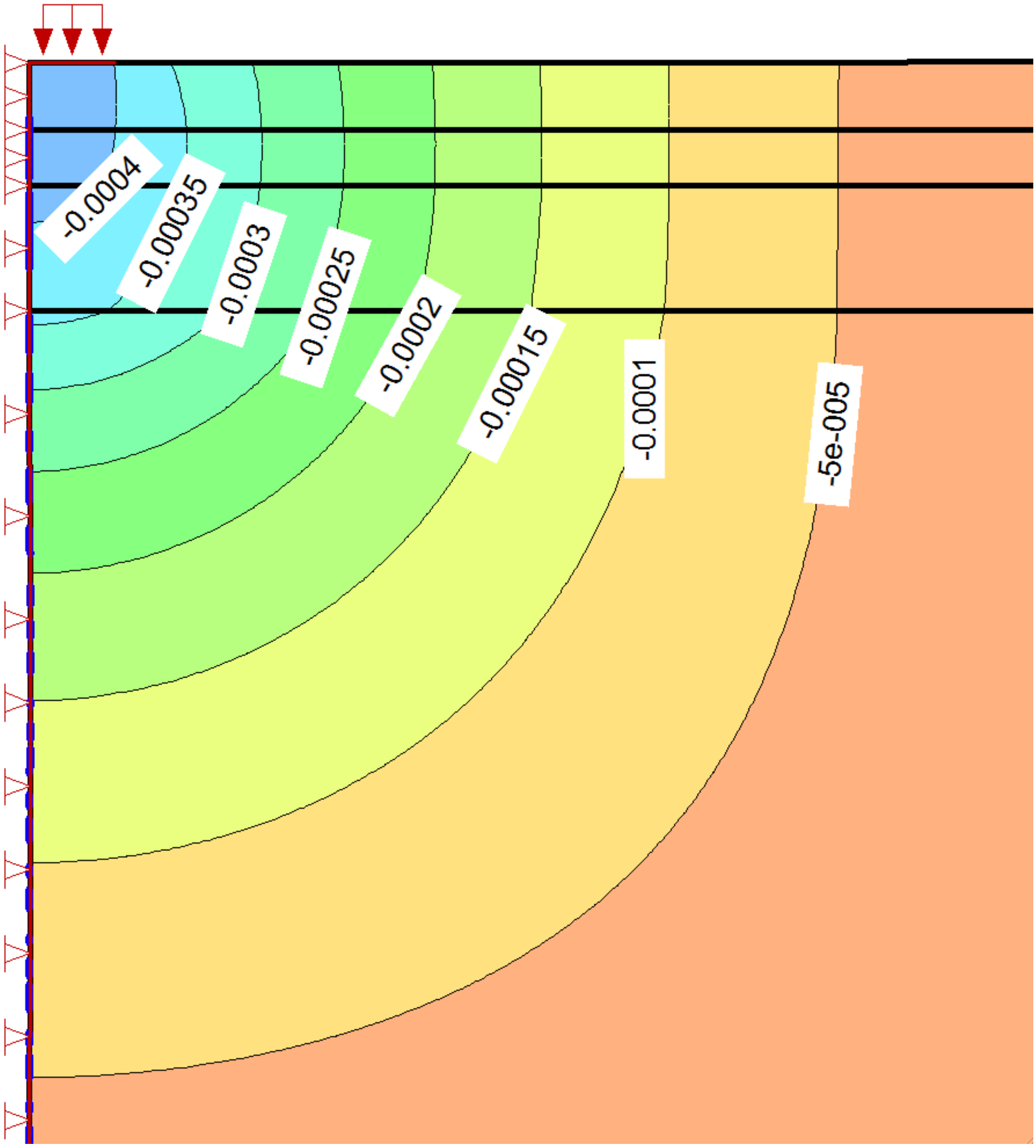
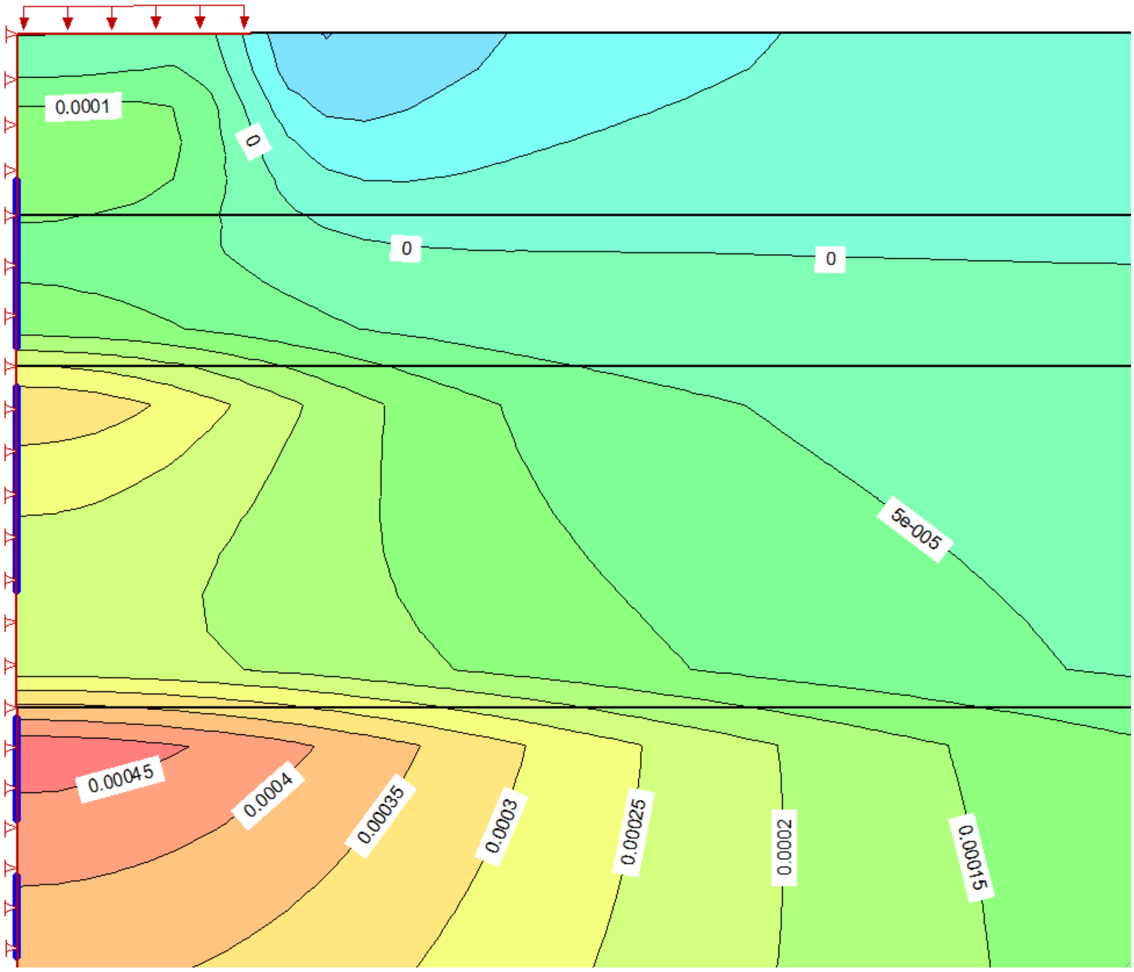
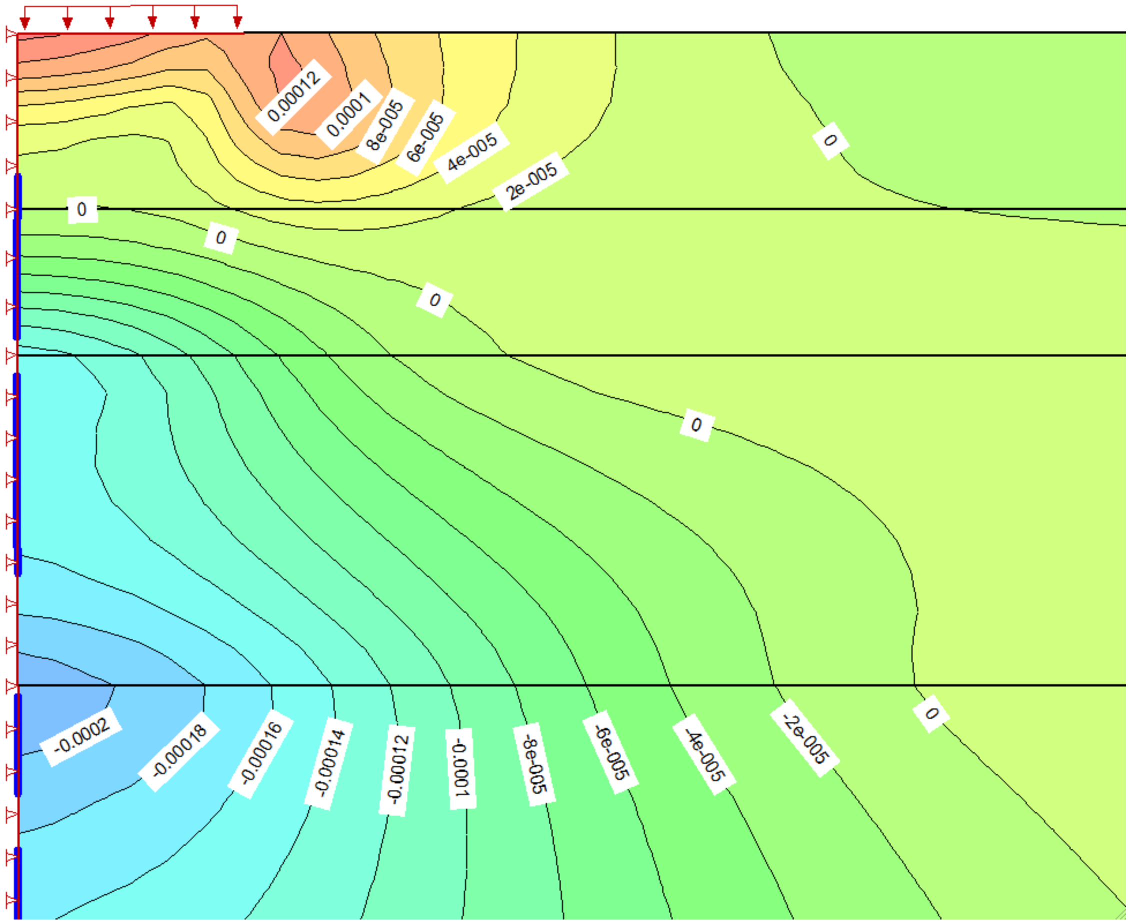


VERTICAL STRAINS

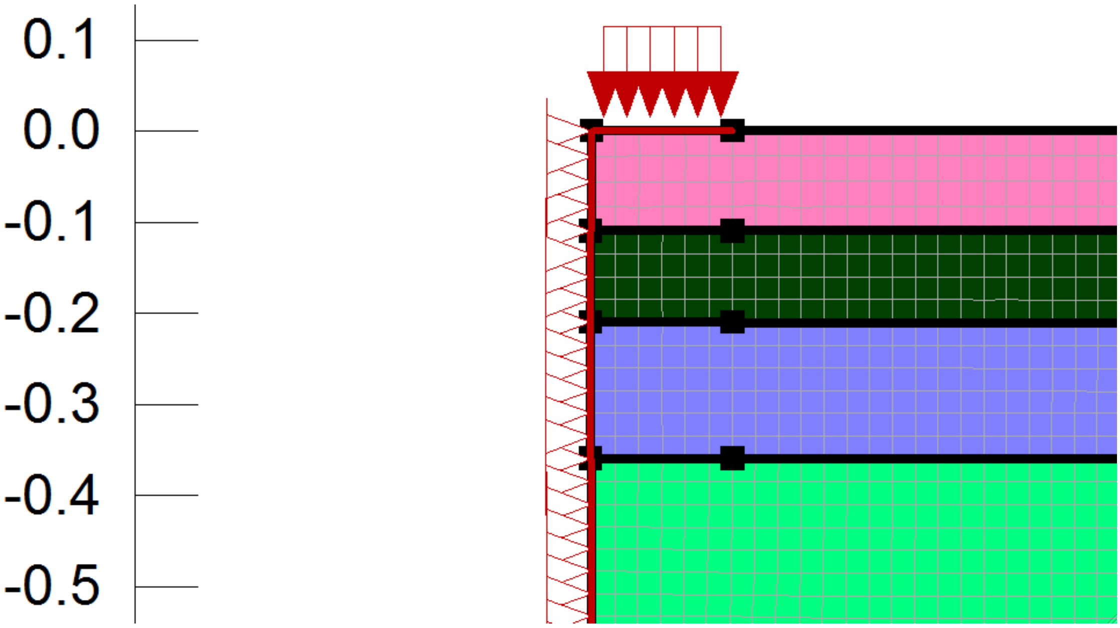


HORIZONTAL STRAINS



BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
EMERGENCY LARGE GOODS VEHICLES ONLY

MODEL



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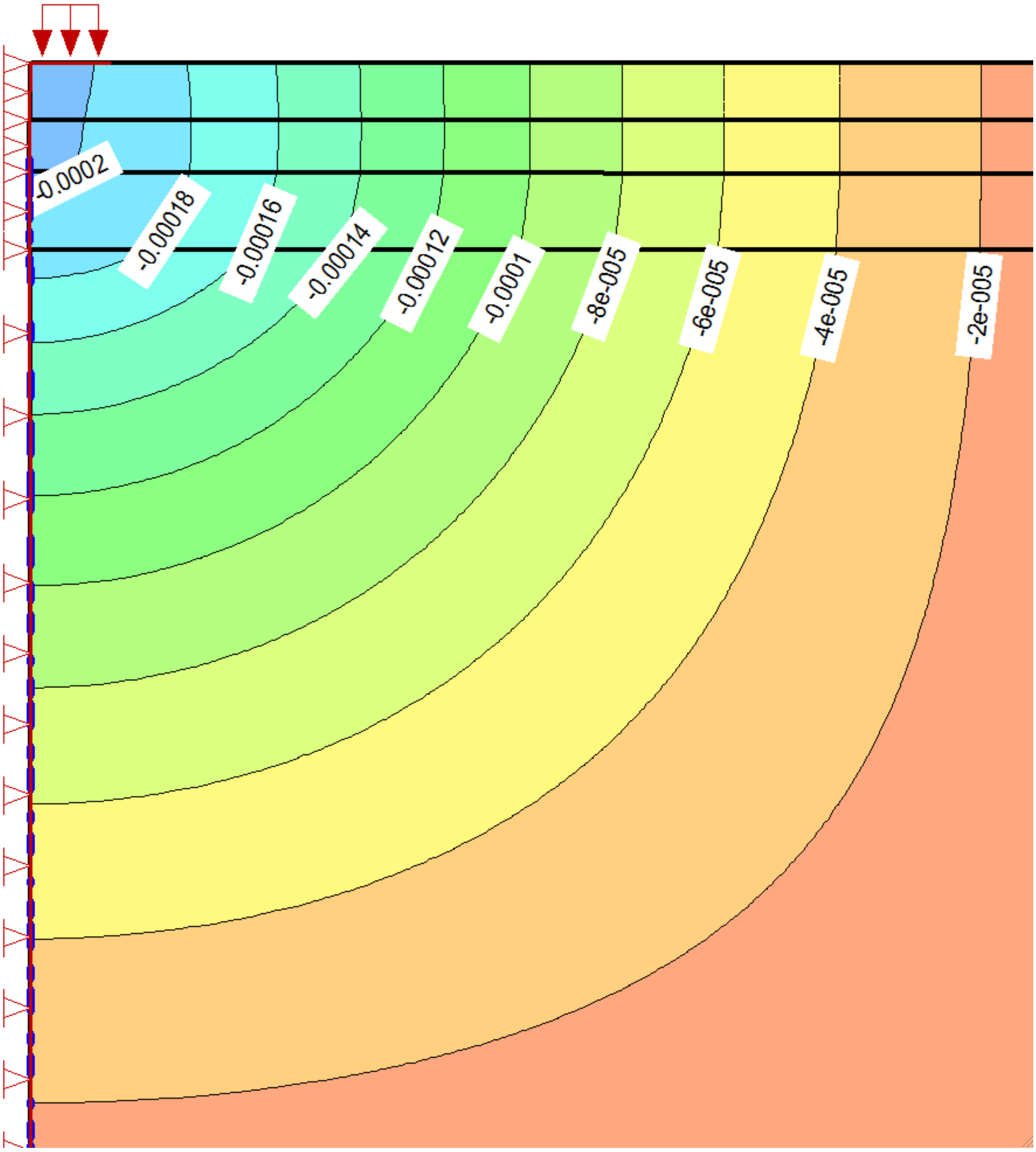
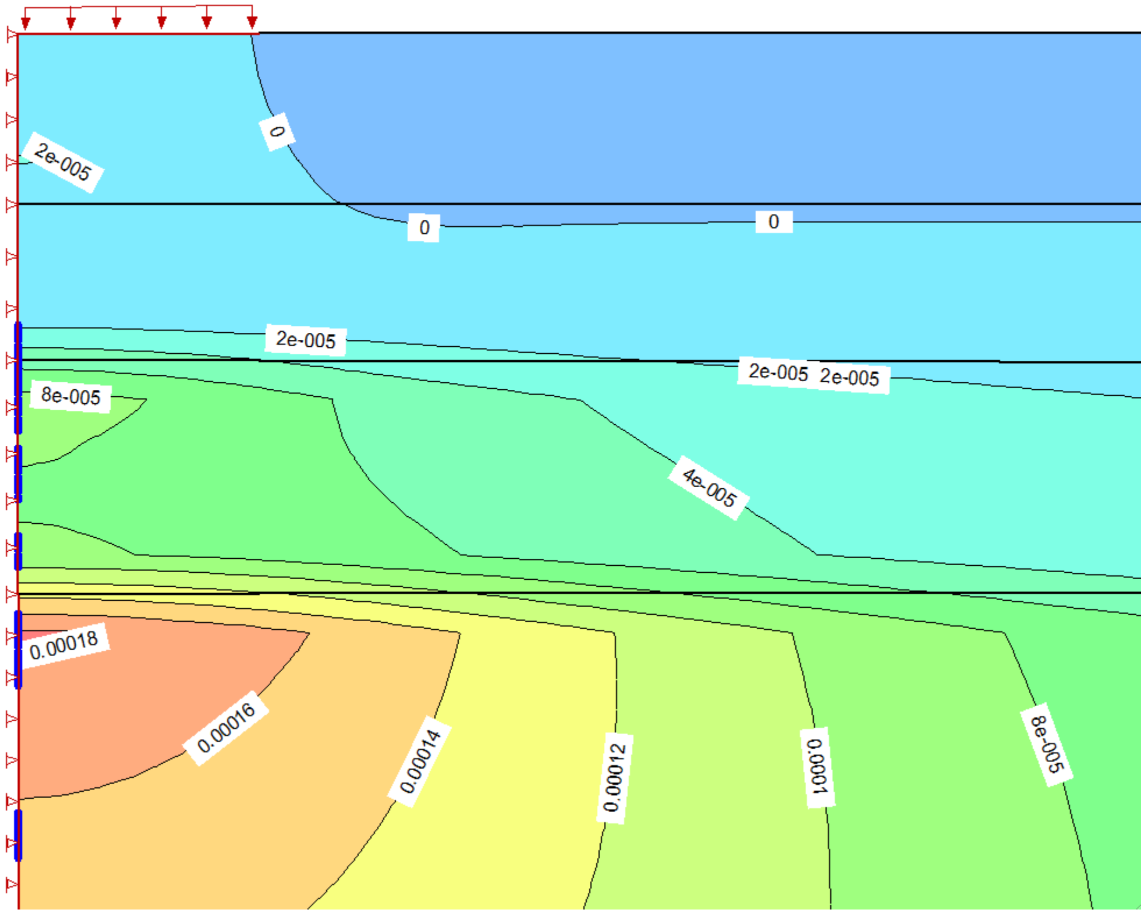
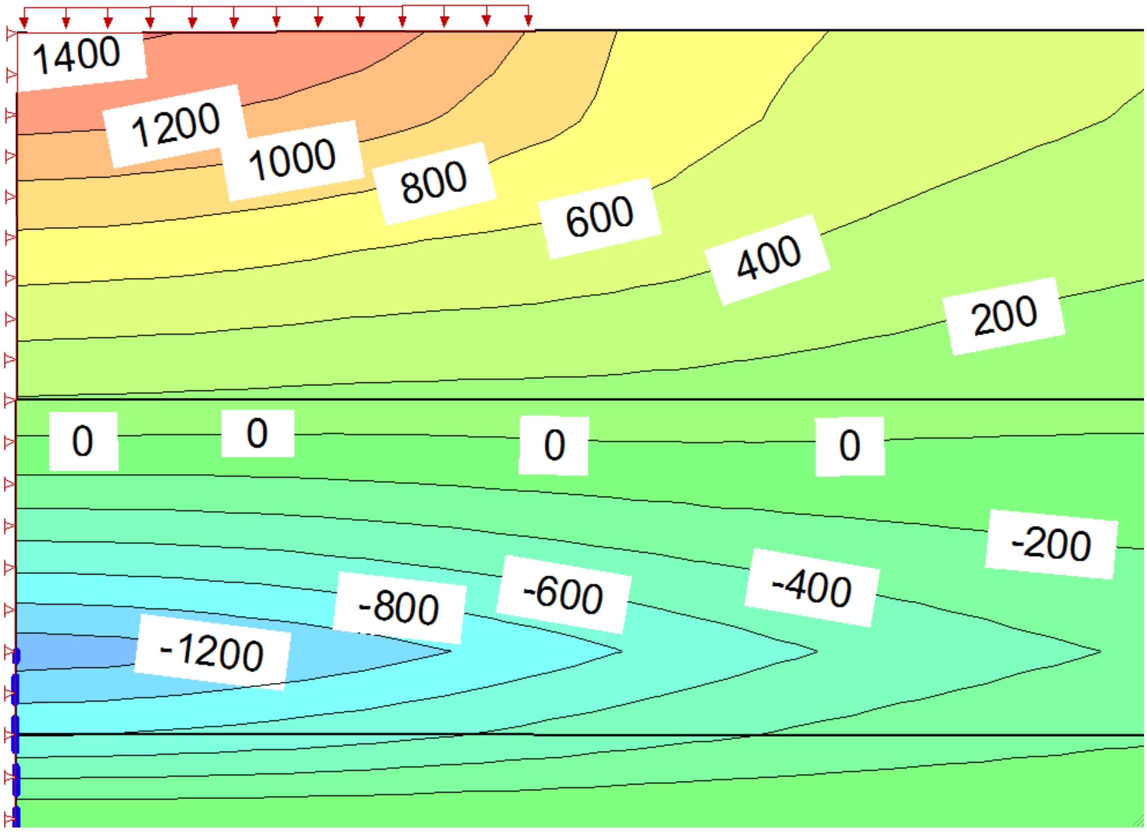


VERTICAL STRAINS

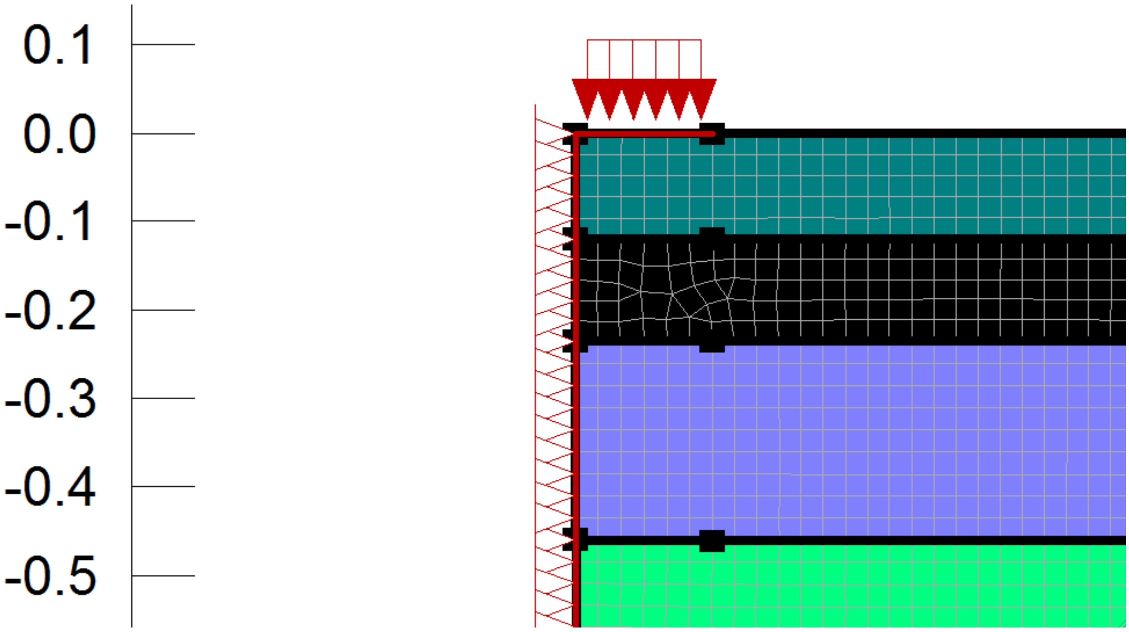


HORIZONTAL STRESSES

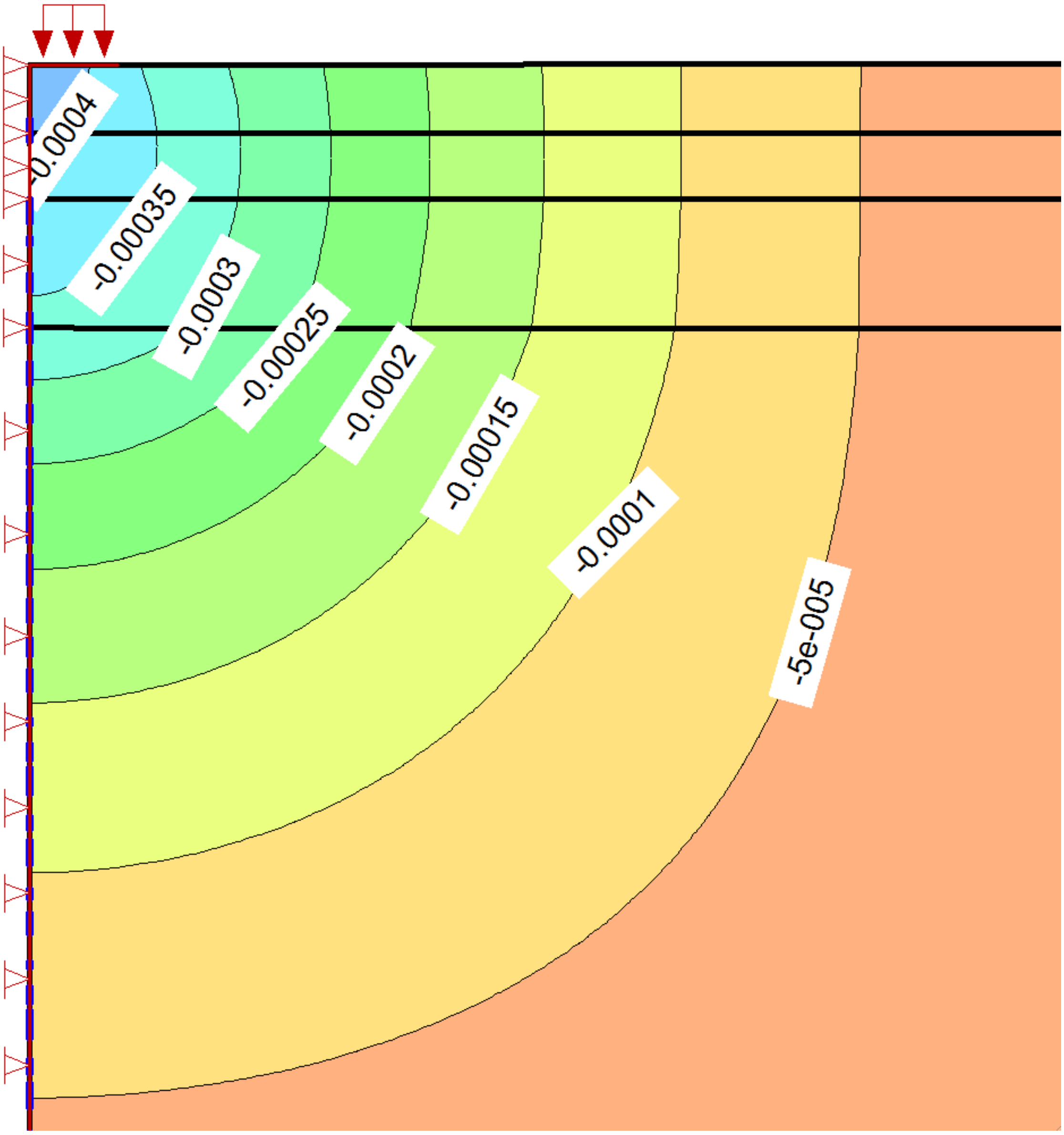


UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
ONE LARGE GOODS VEHICLE PER WEEK (0.015MSA)

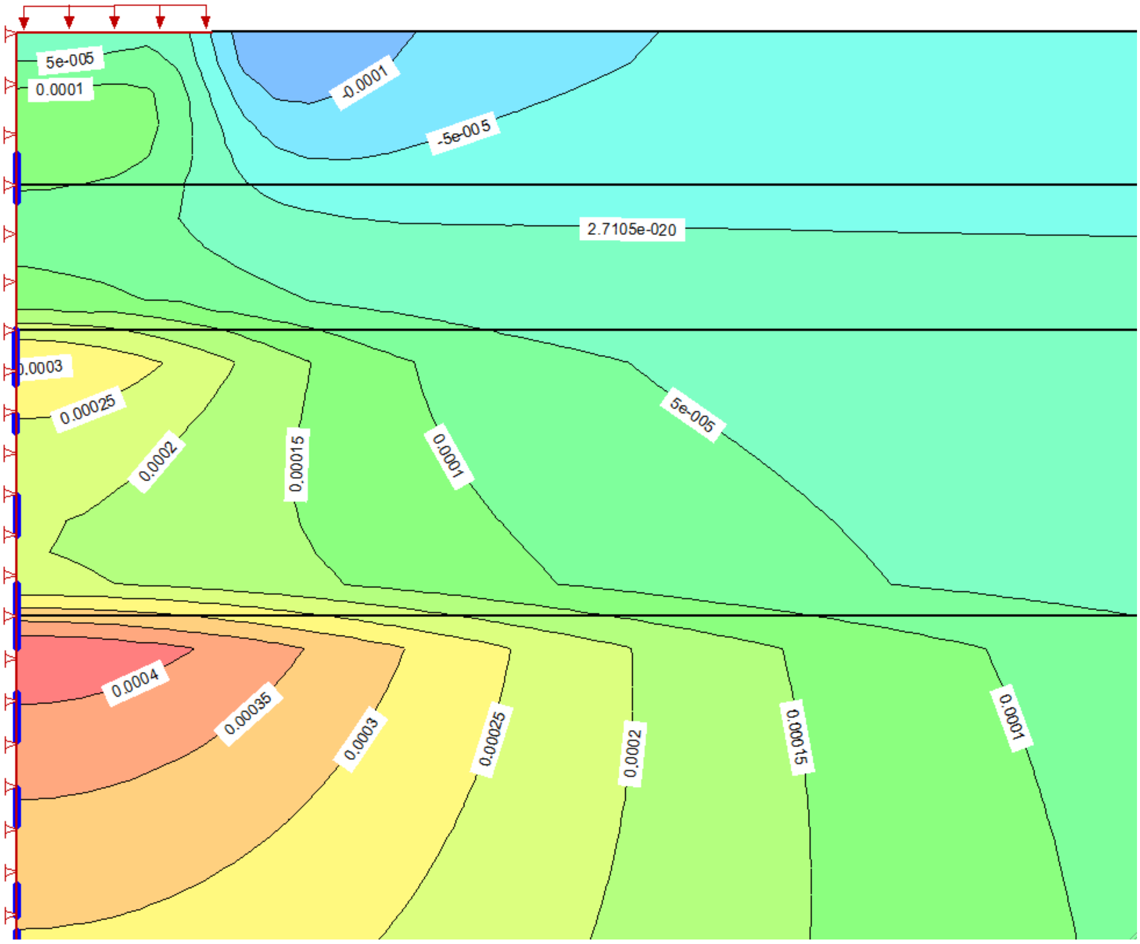
MODEL



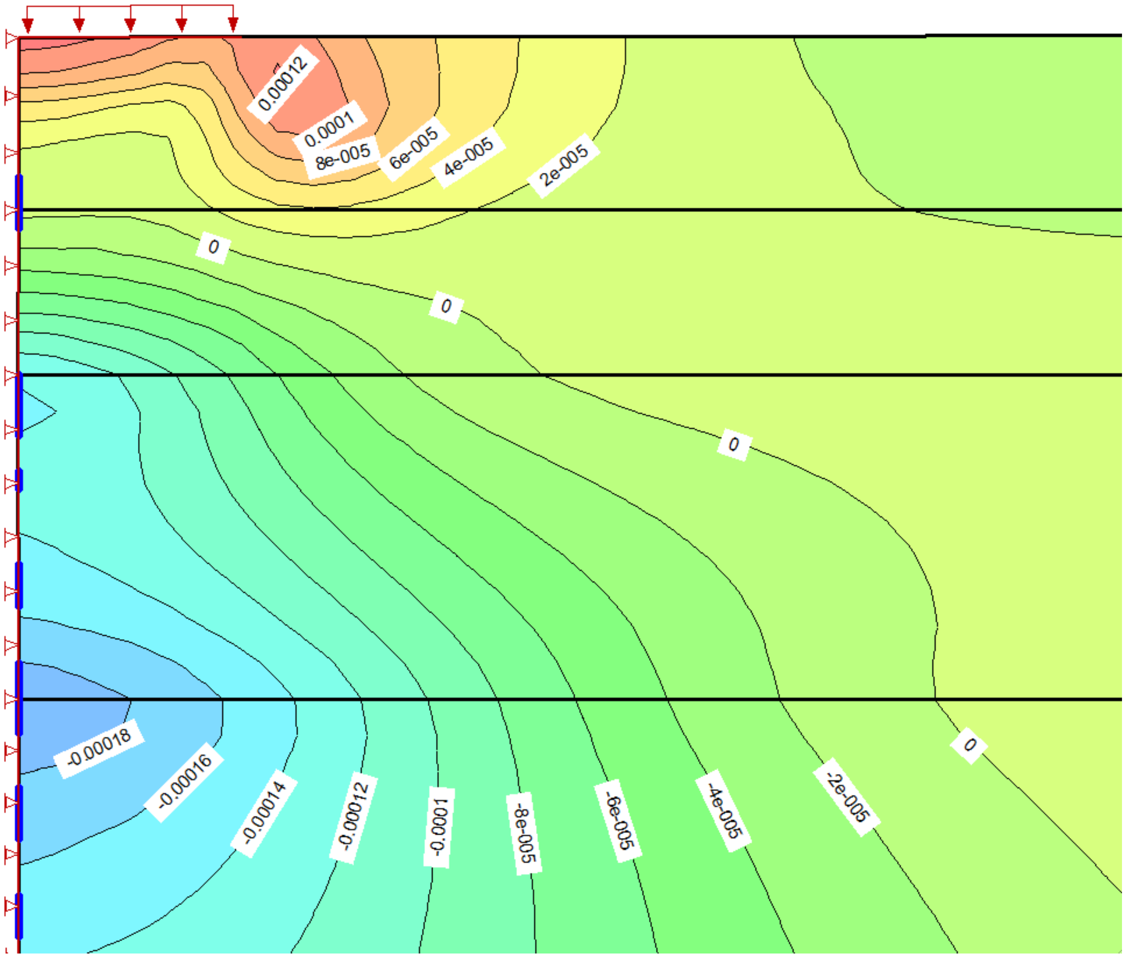
VERTICAL DEFLECTIONS



VERTICAL STRAINS

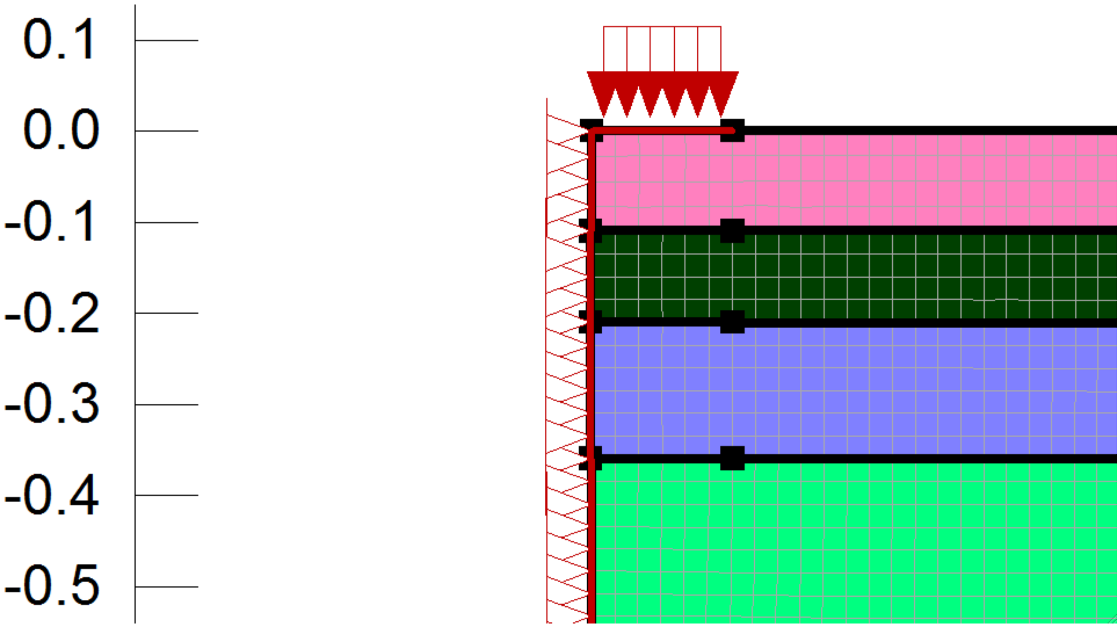


HORIZONTAL STRAINS

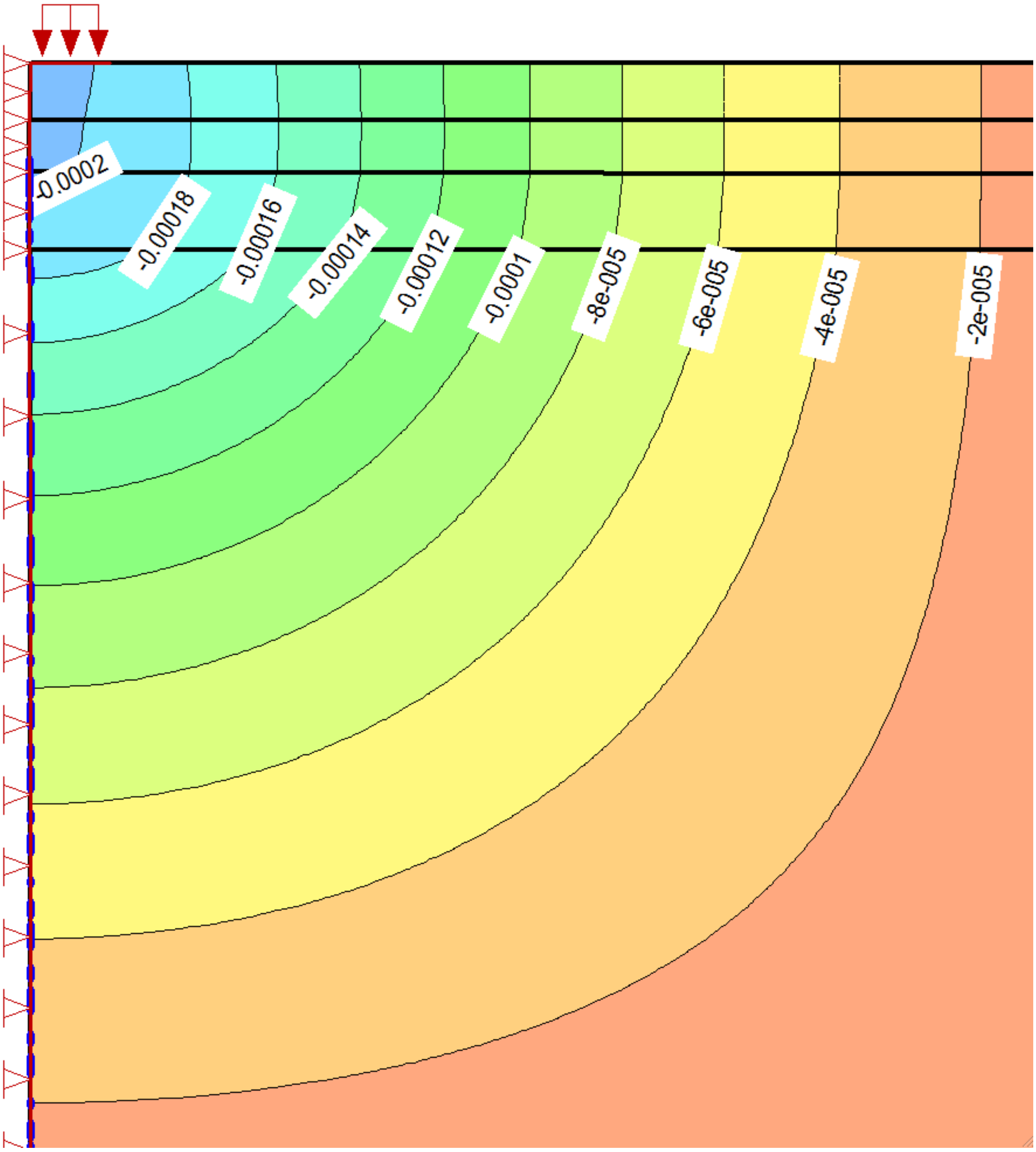


BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
ONE LARGE GOODS VEHICLE PER WEEK (0.015MSA)

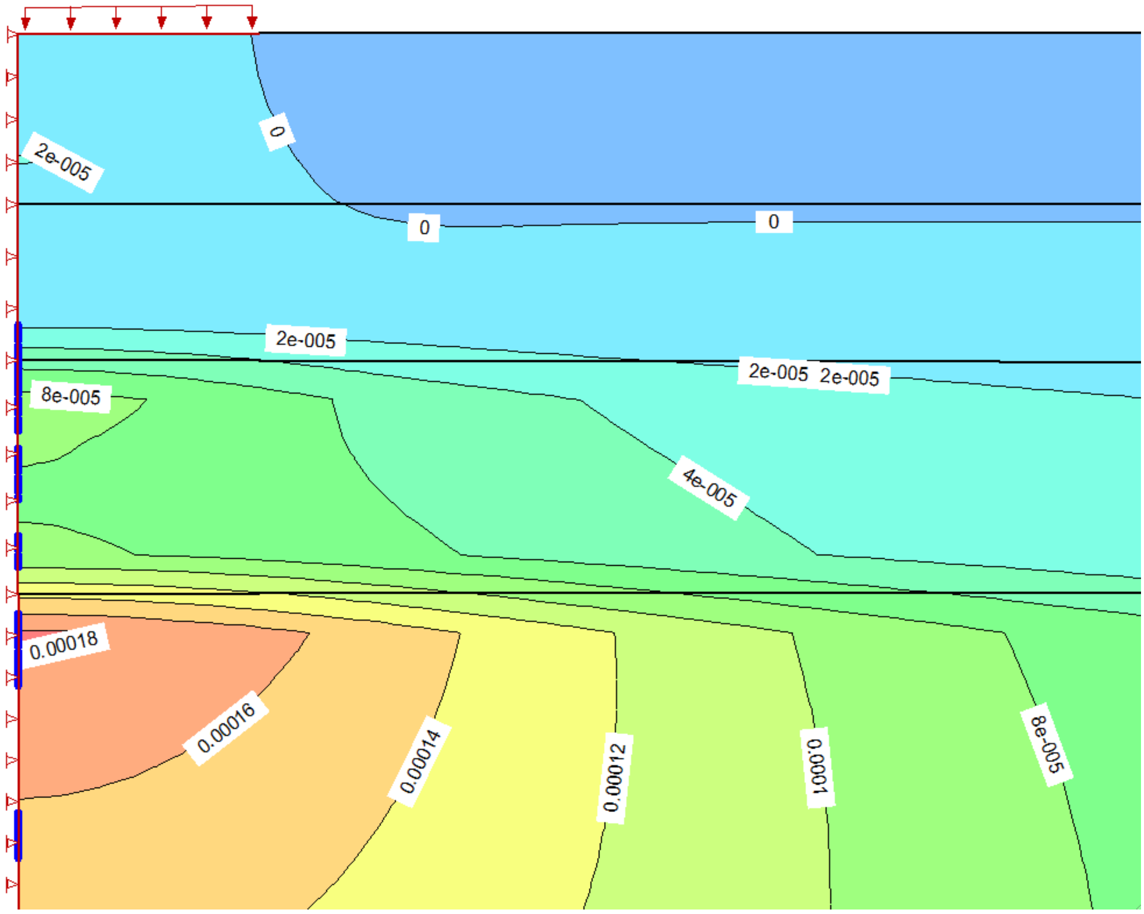
MODEL



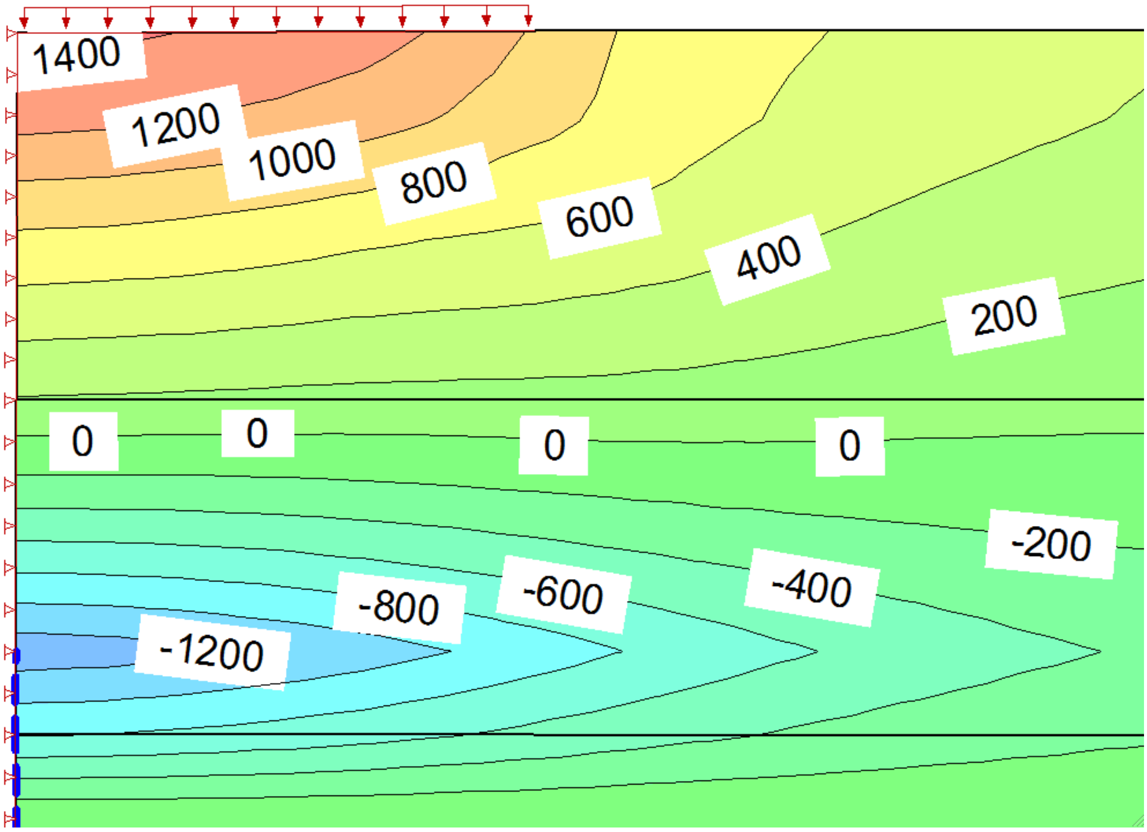
VERTICAL DEFLECTIONS



VERTICAL STRAINS

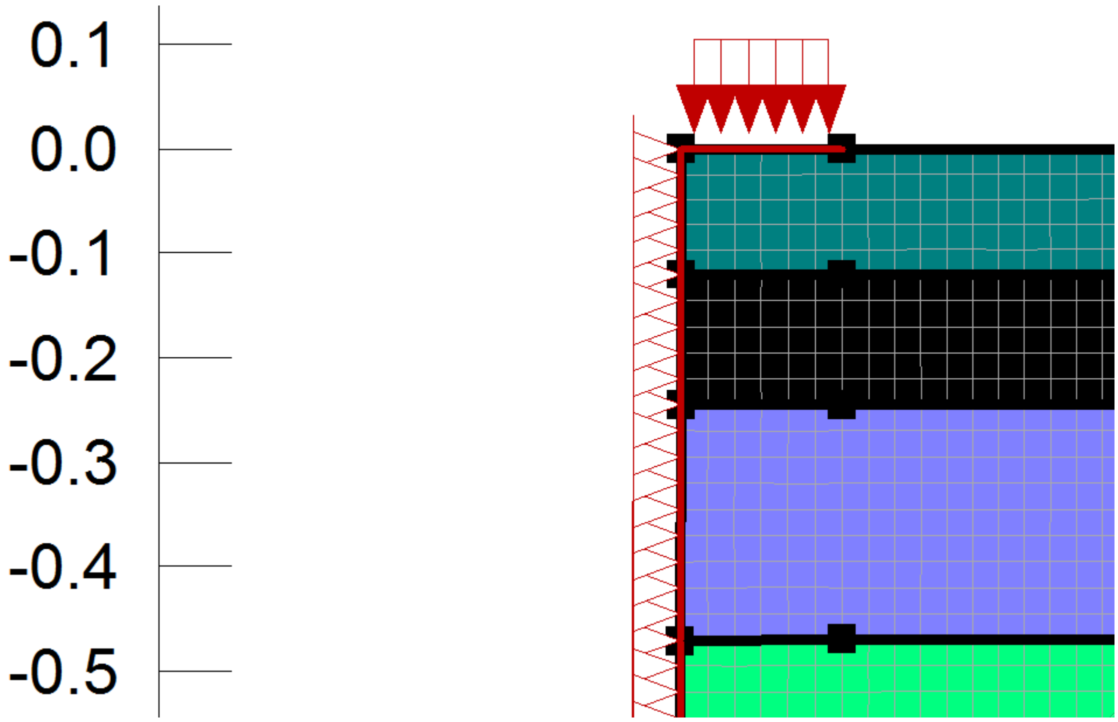


HORIZONTAL STRESSES

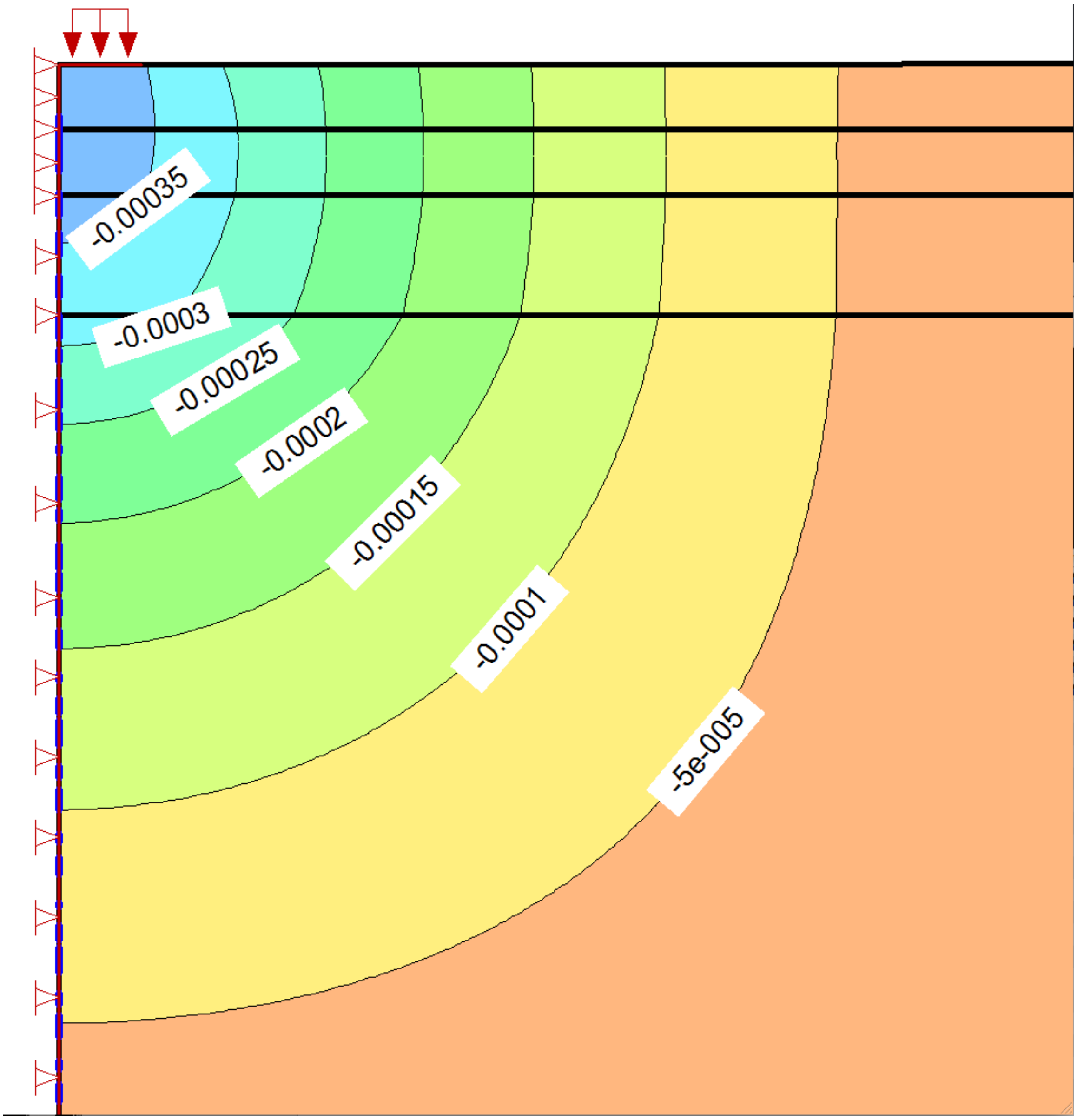


UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
TEN LARGE GOODS VEHICLES PER WEEK (0.15MSA)

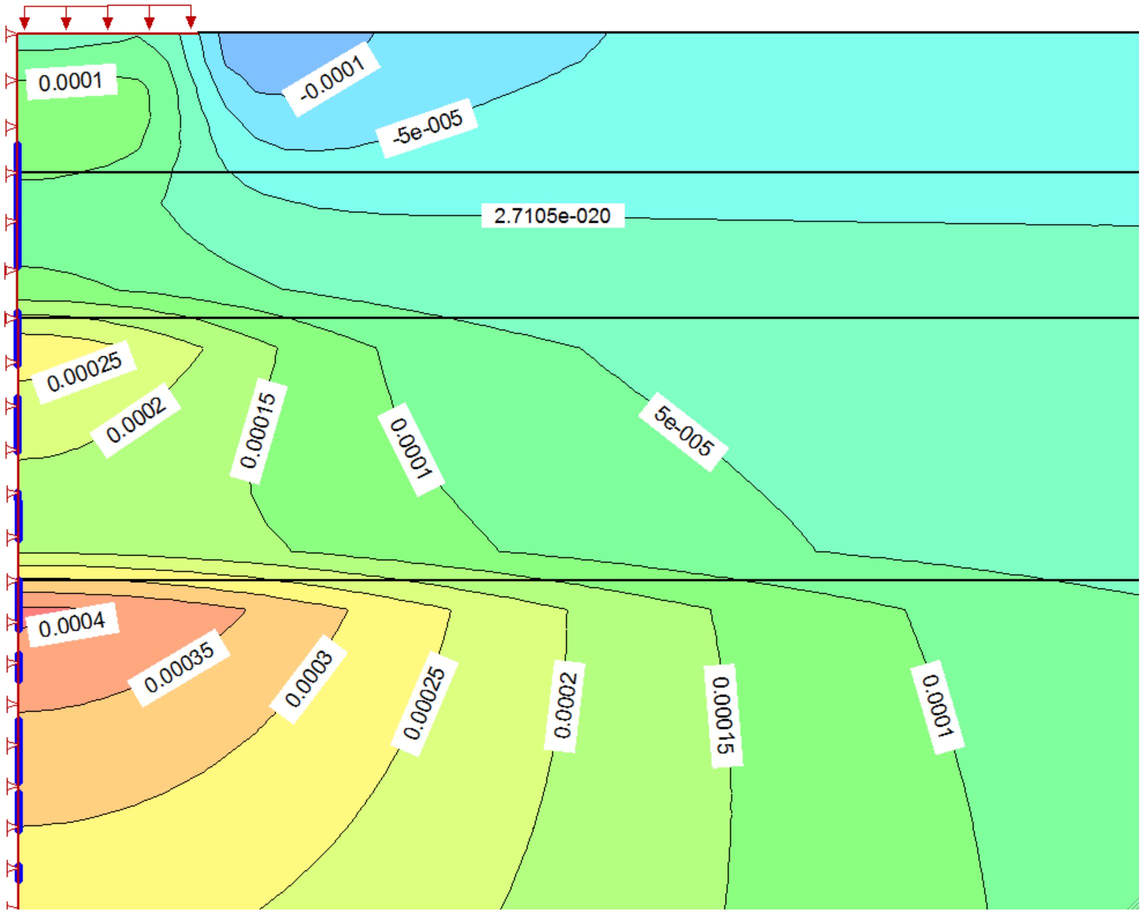
MODEL



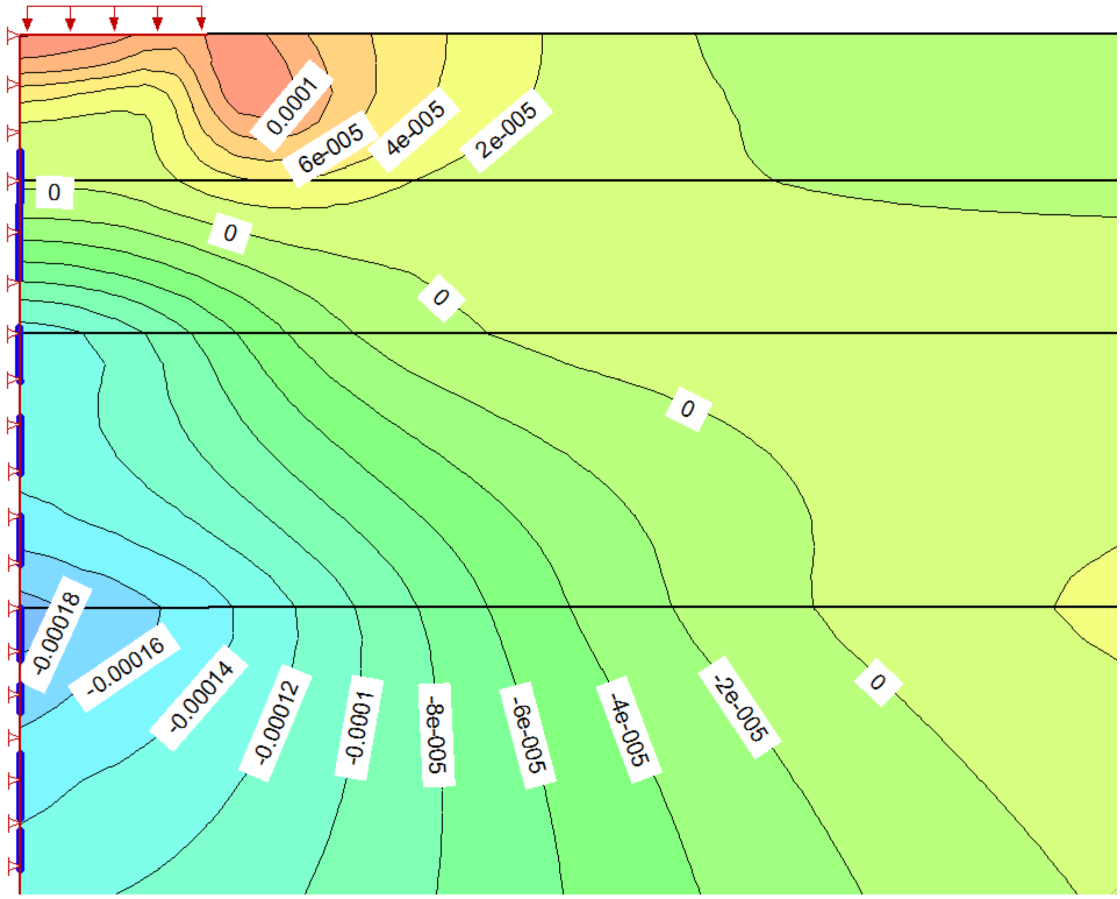
VERTICAL DEFLECTIONS



VERTICAL STRAINS

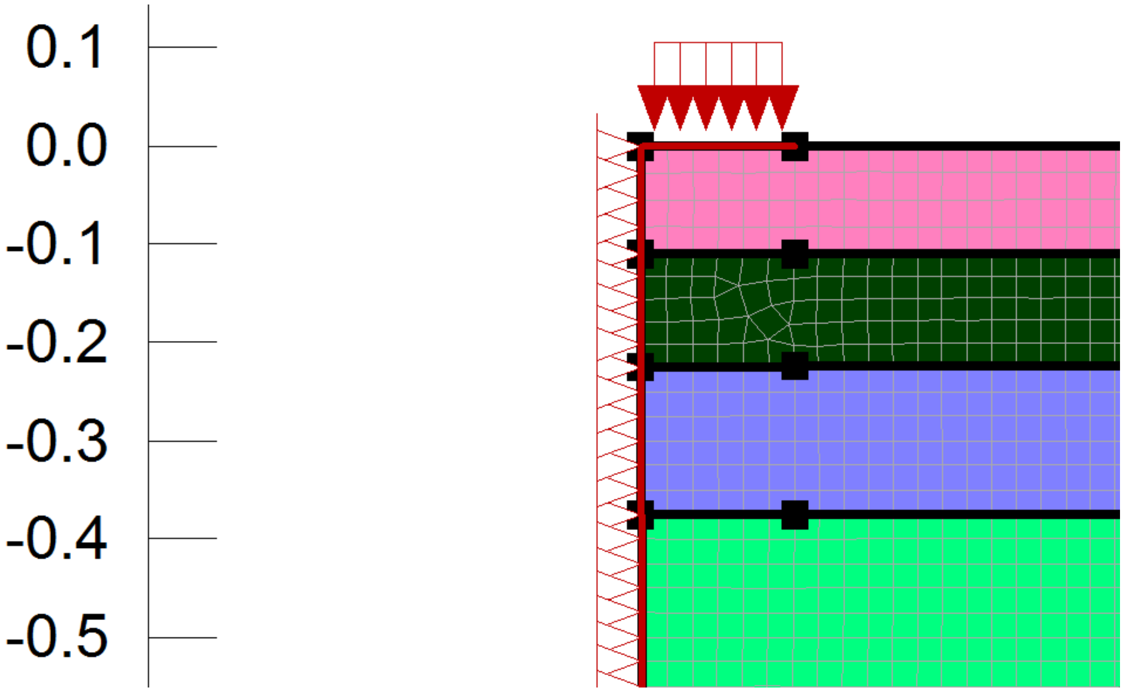


HORIZONTAL STRAINS

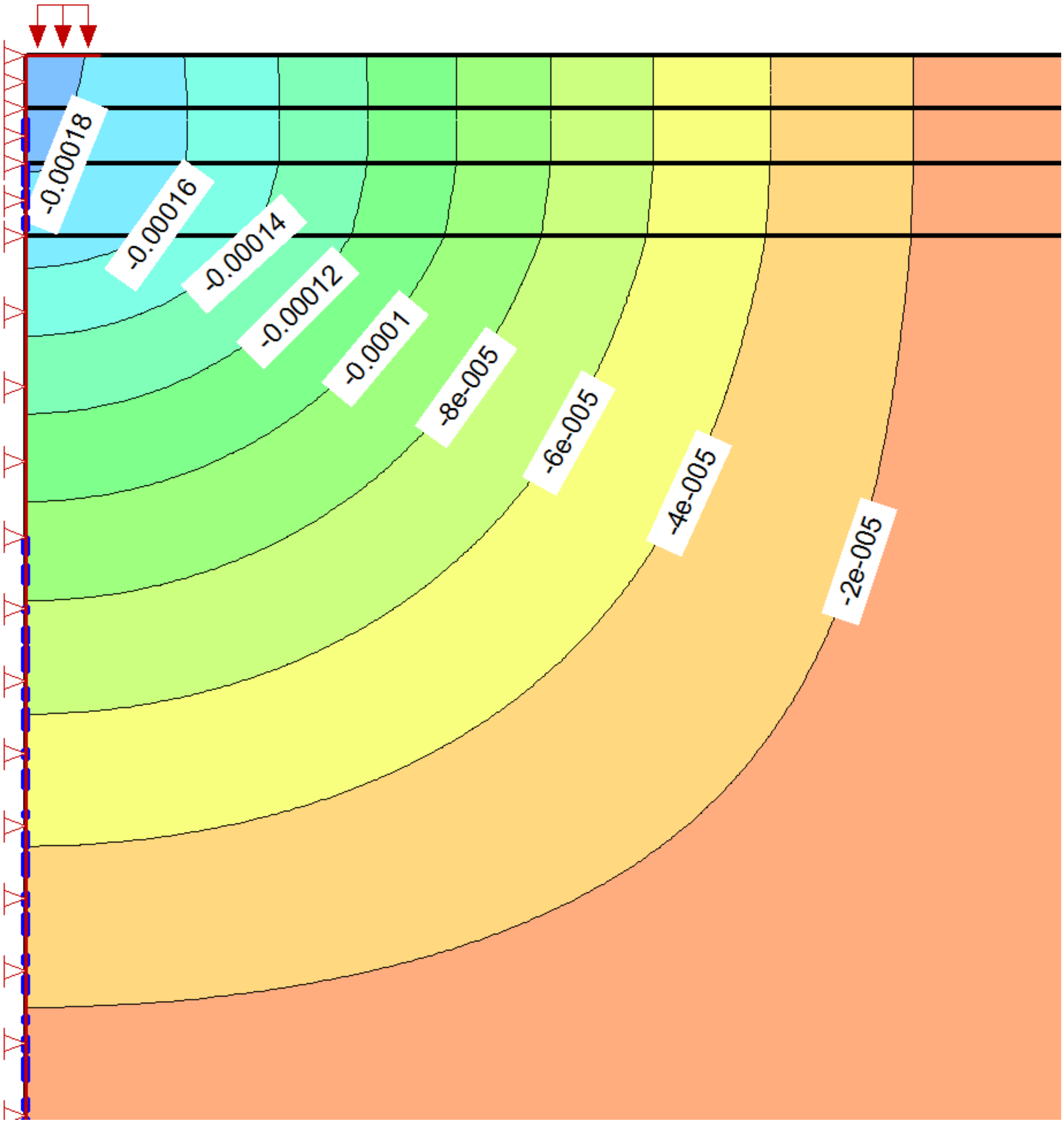


BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
TEN LARGE GOODS VEHICLES PER WEEK (0.15MSA)

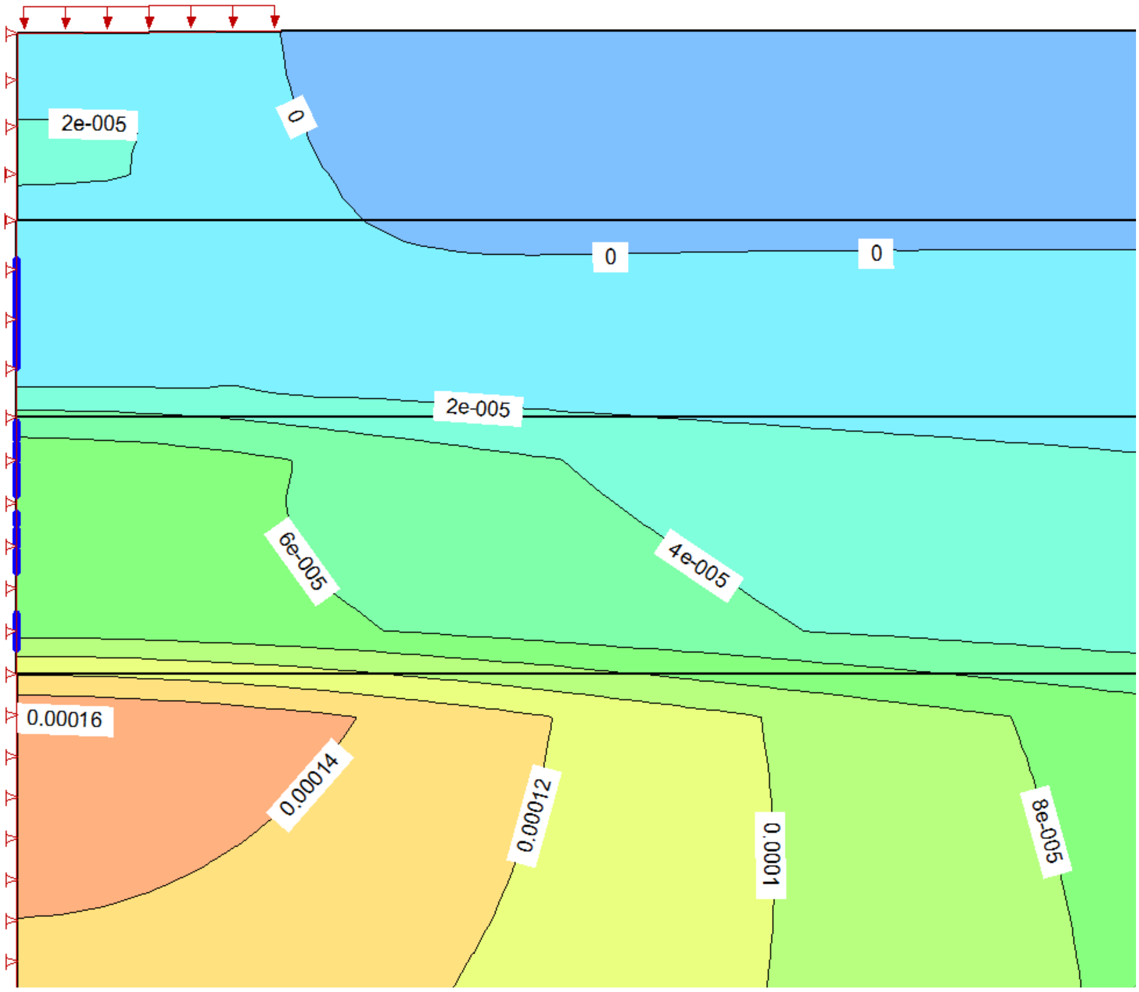
MODEL



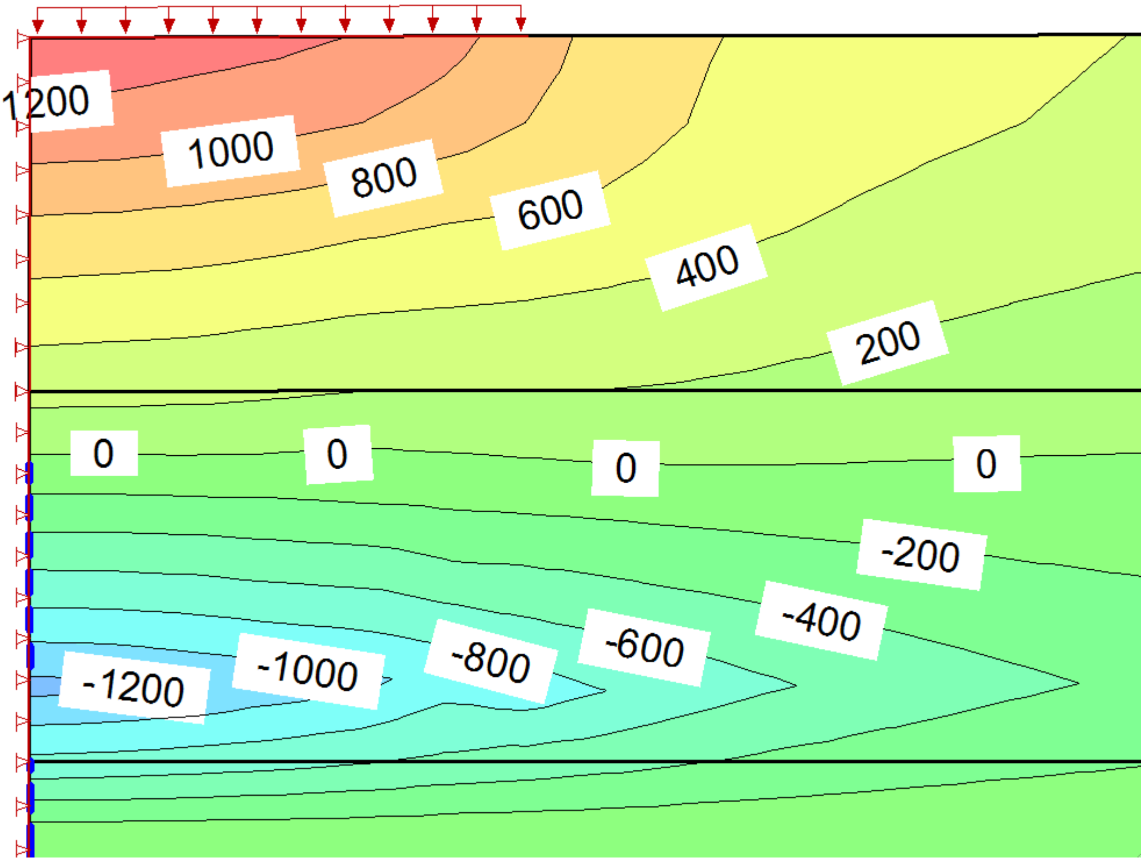
VERTICAL DEFLECTIONS



VERTICAL STRAINS

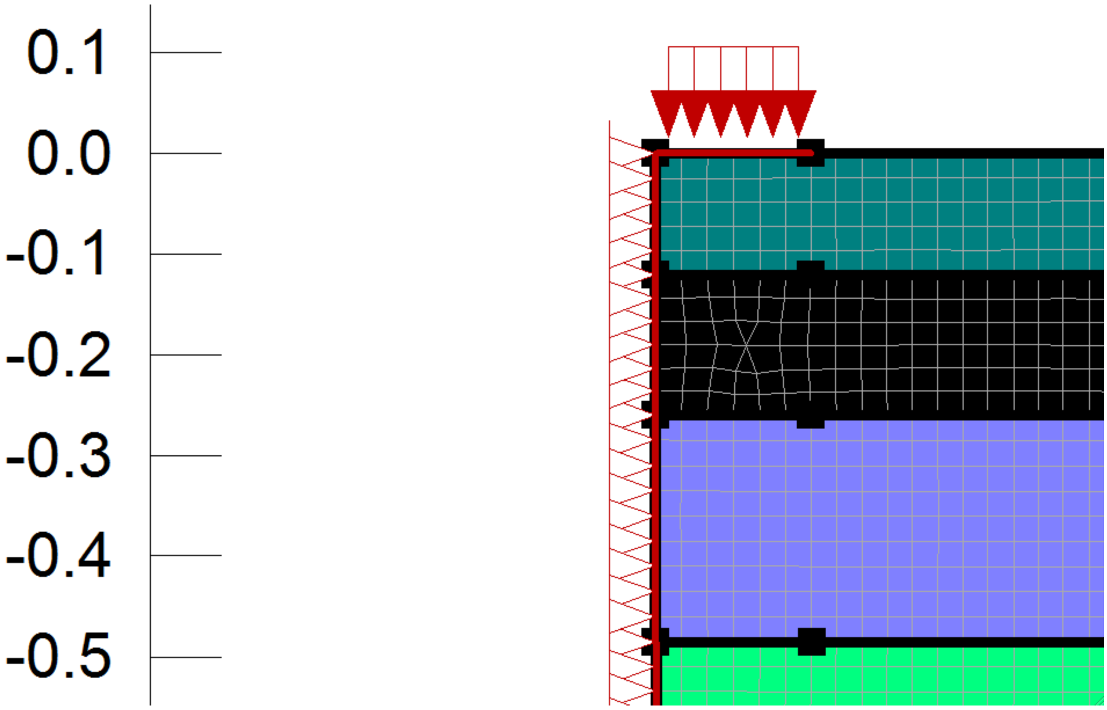


HORIZONTAL STRESSES

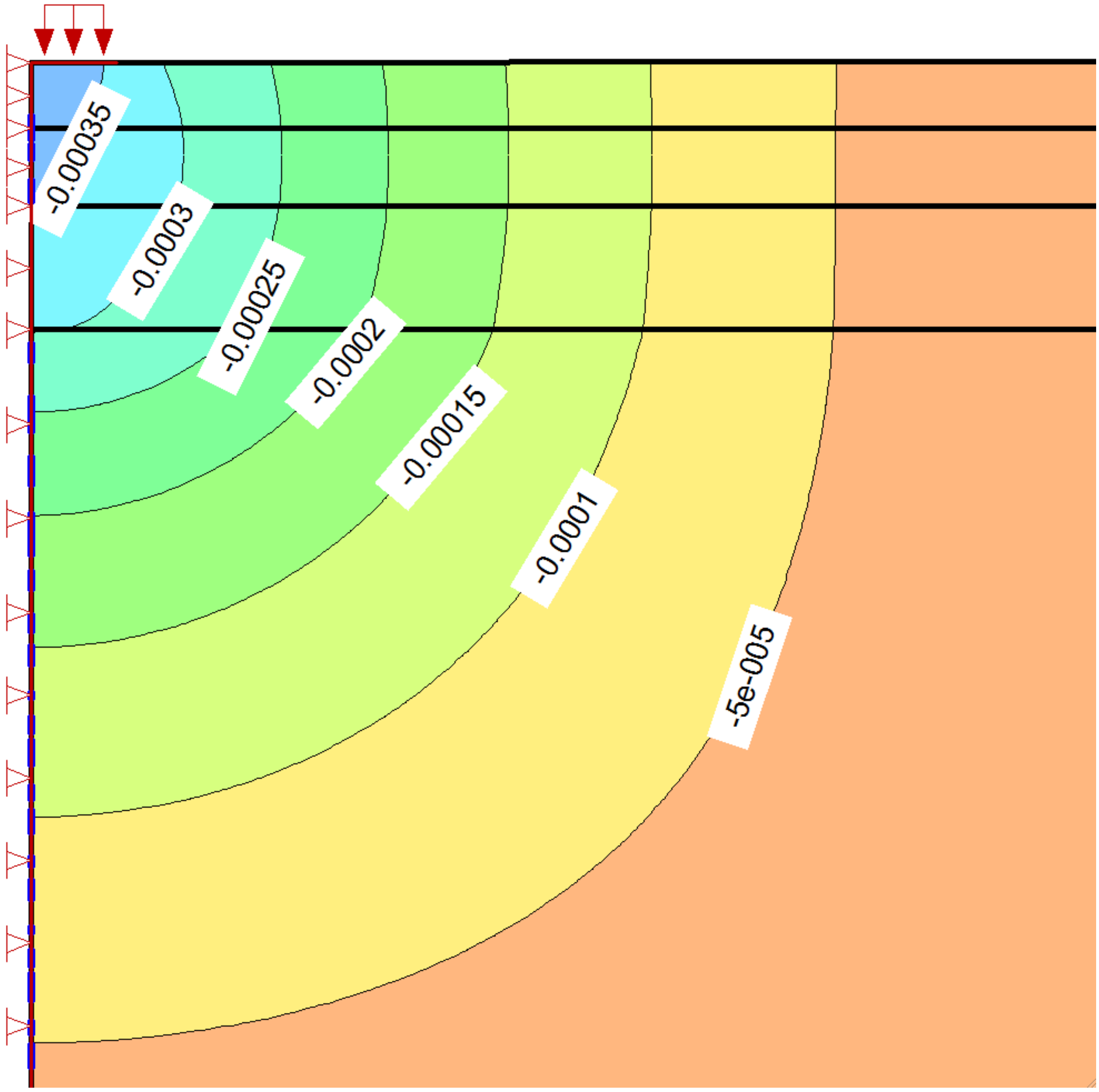


UNBOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
100 LARGE GOODS VEHICLES PER WEEK

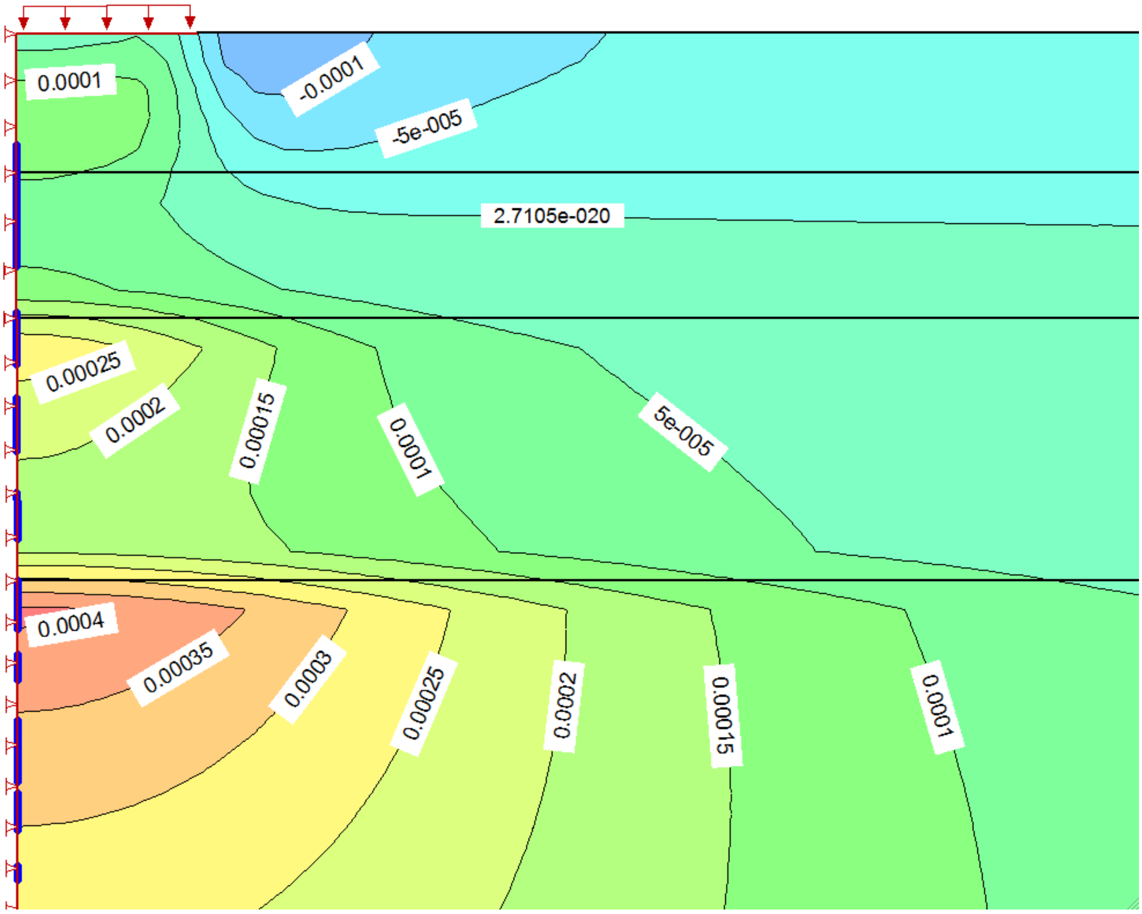
MODEL



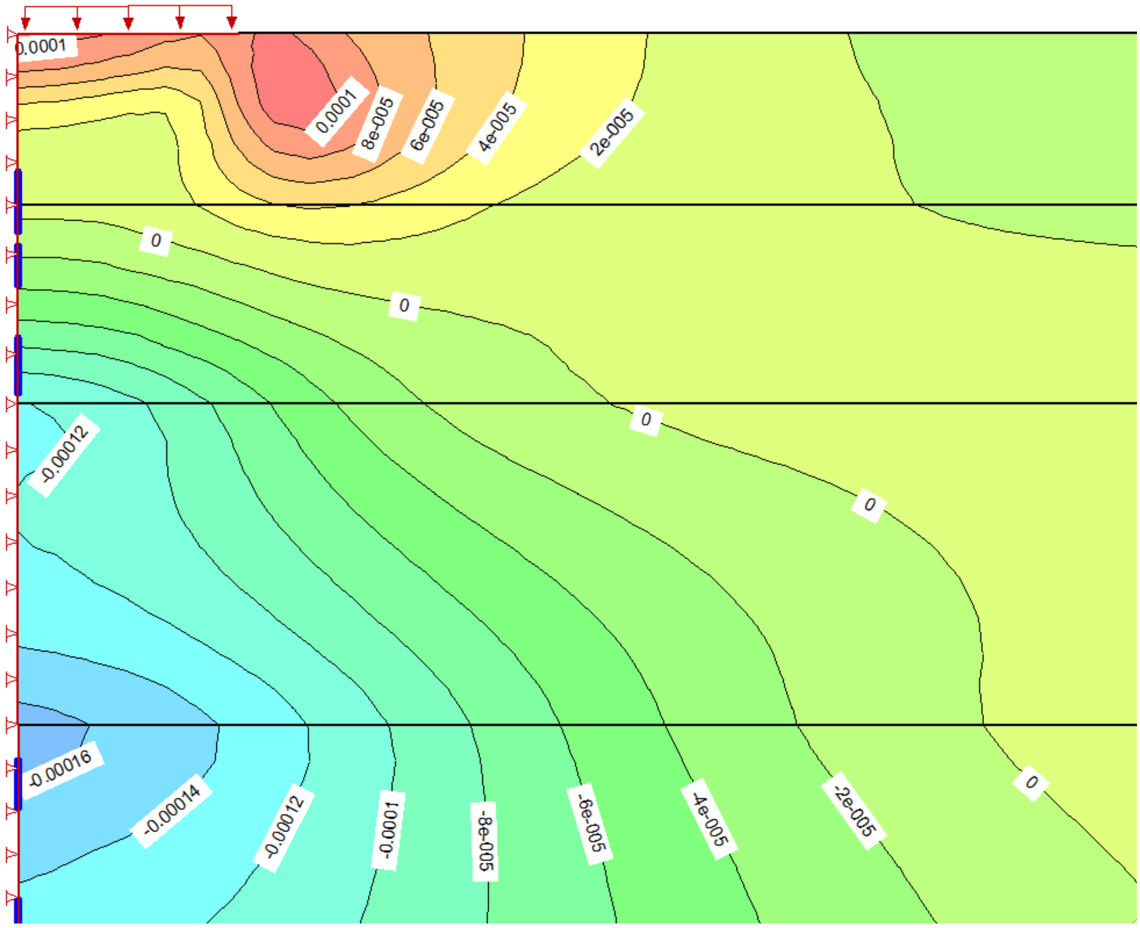
VERTICAL DEFLECTIONS



VERTICAL STRAINS

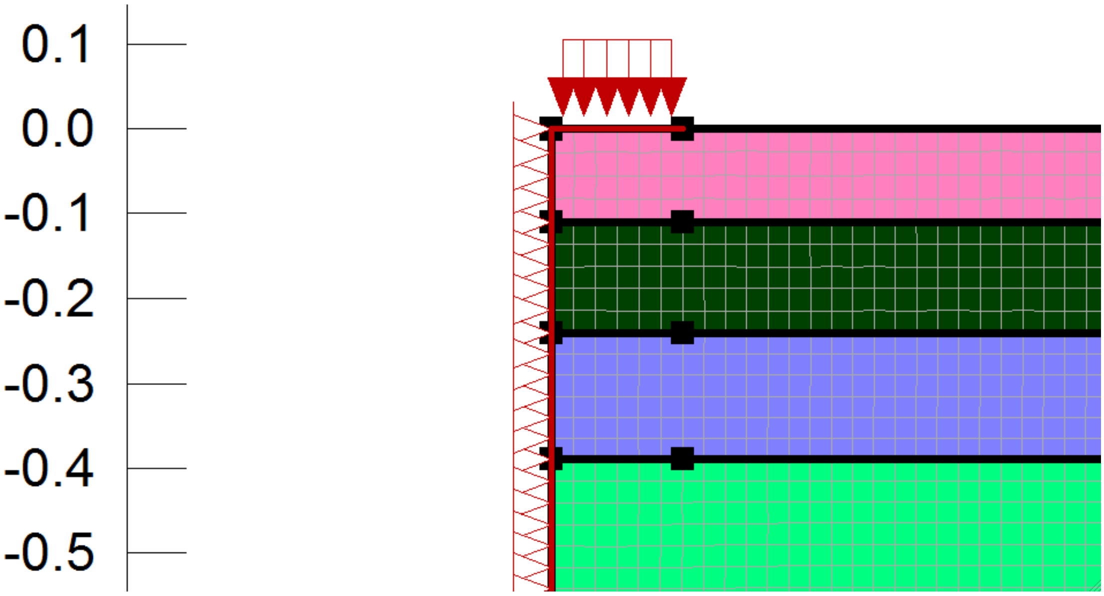


HORIZONTAL STRAINS

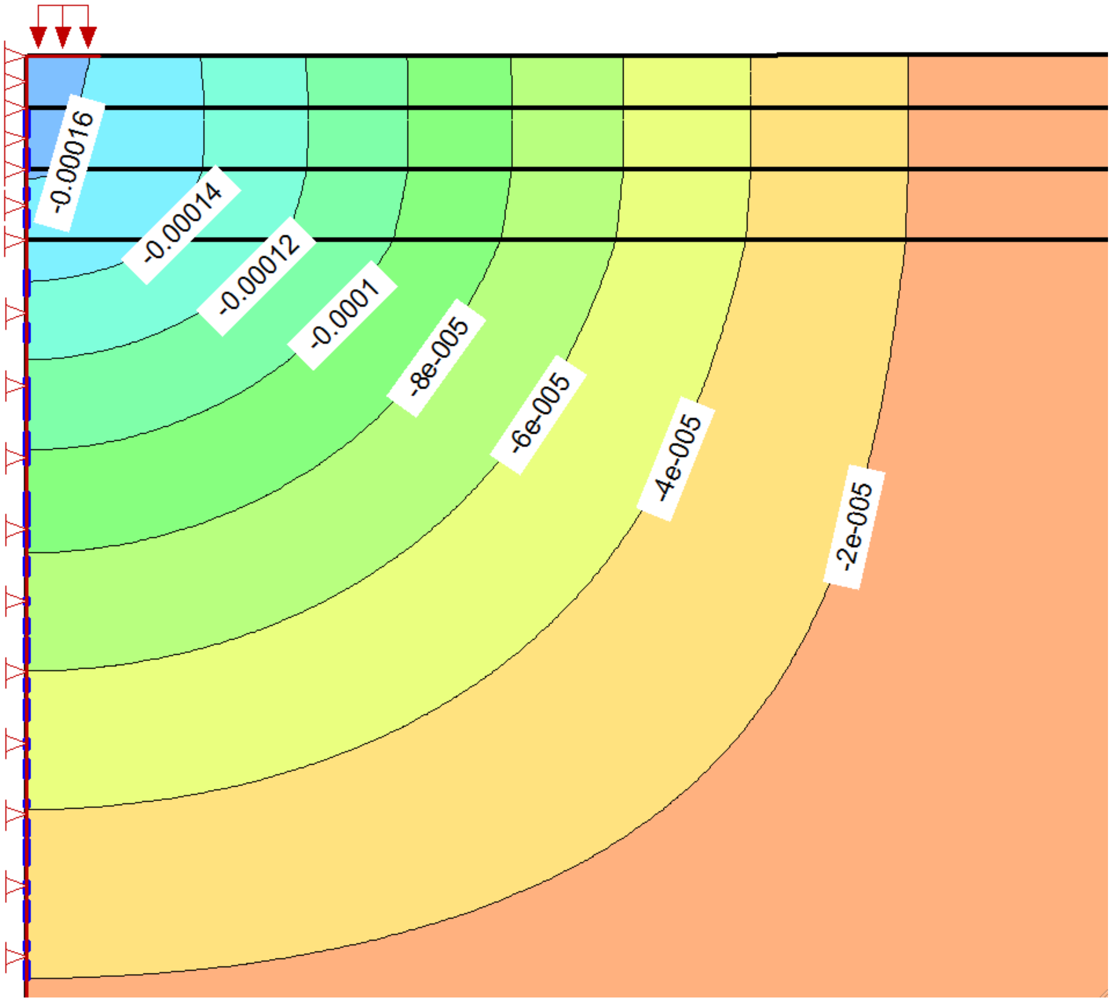


BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
100 LARGE GOODS VEHICLES PER WEEK

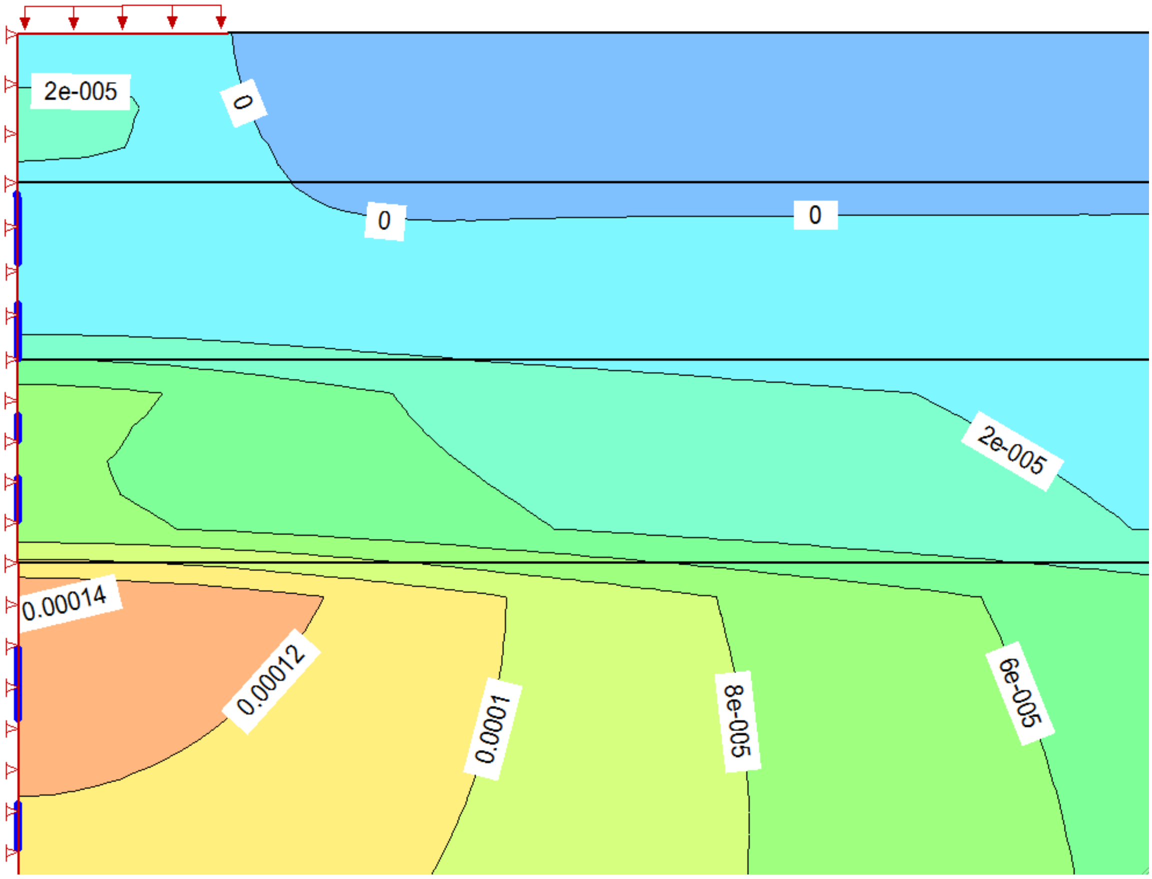
MODEL



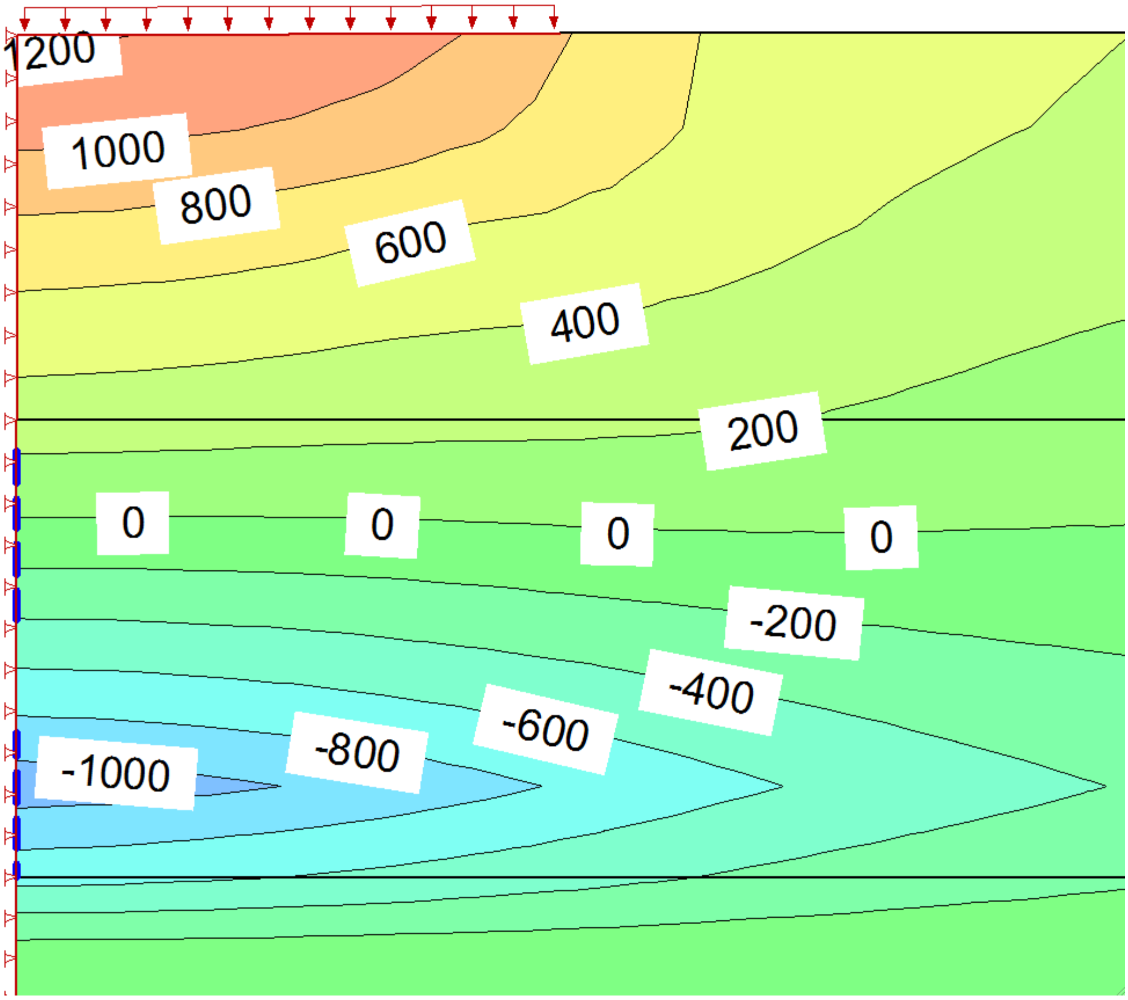
VERTICAL DEFLECTIONS



VERTICAL STRAINS

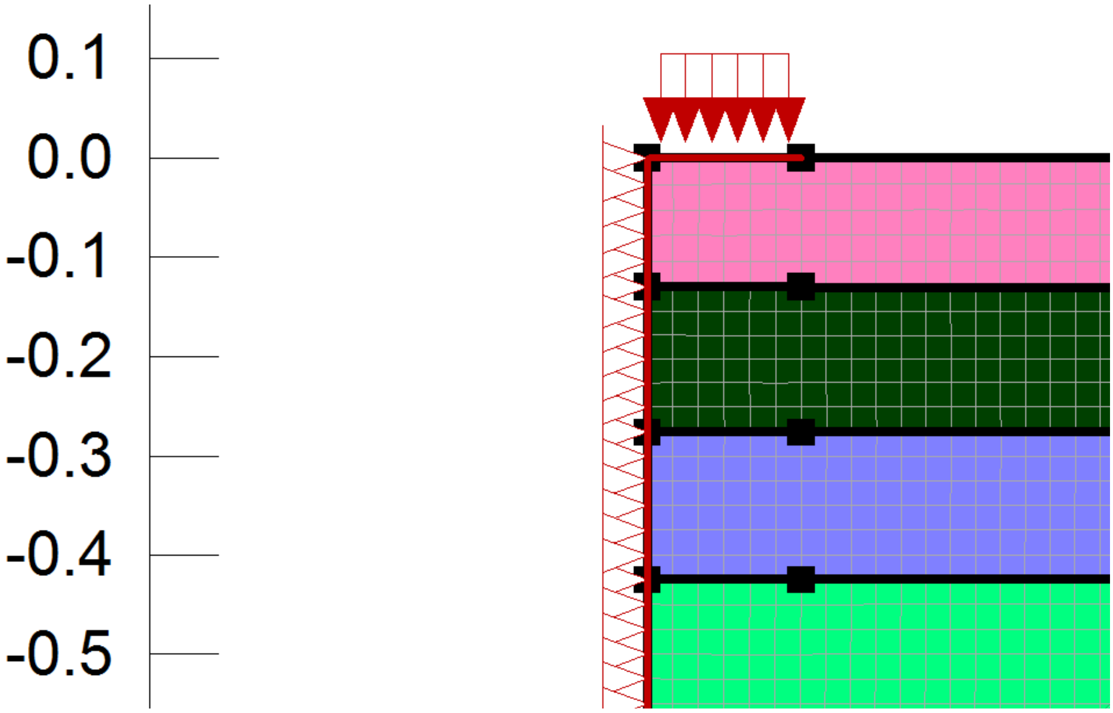


HORIZONTAL STRESSES

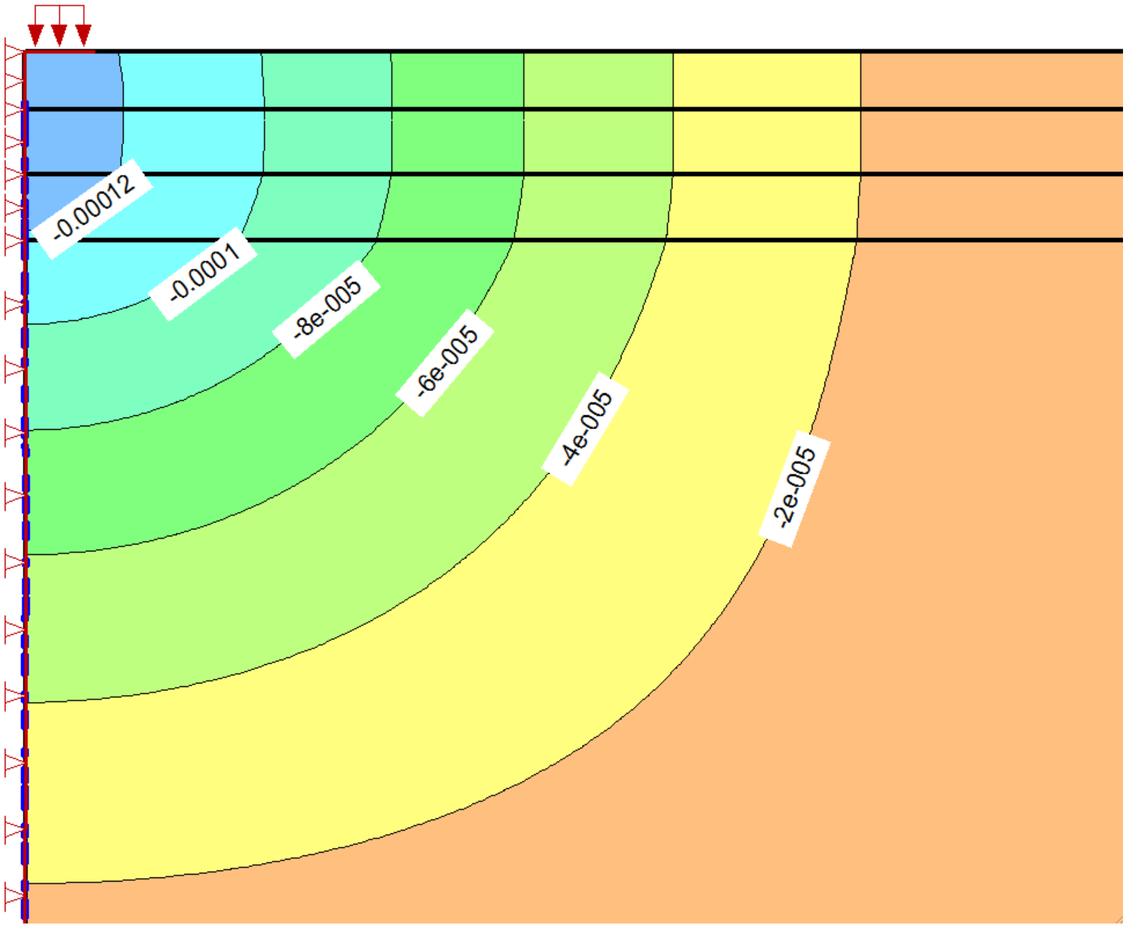


BOUND SURFACE RIGID BASE PIETRA PAVE PAVEMENTS 1.5MSA TO 4MSA

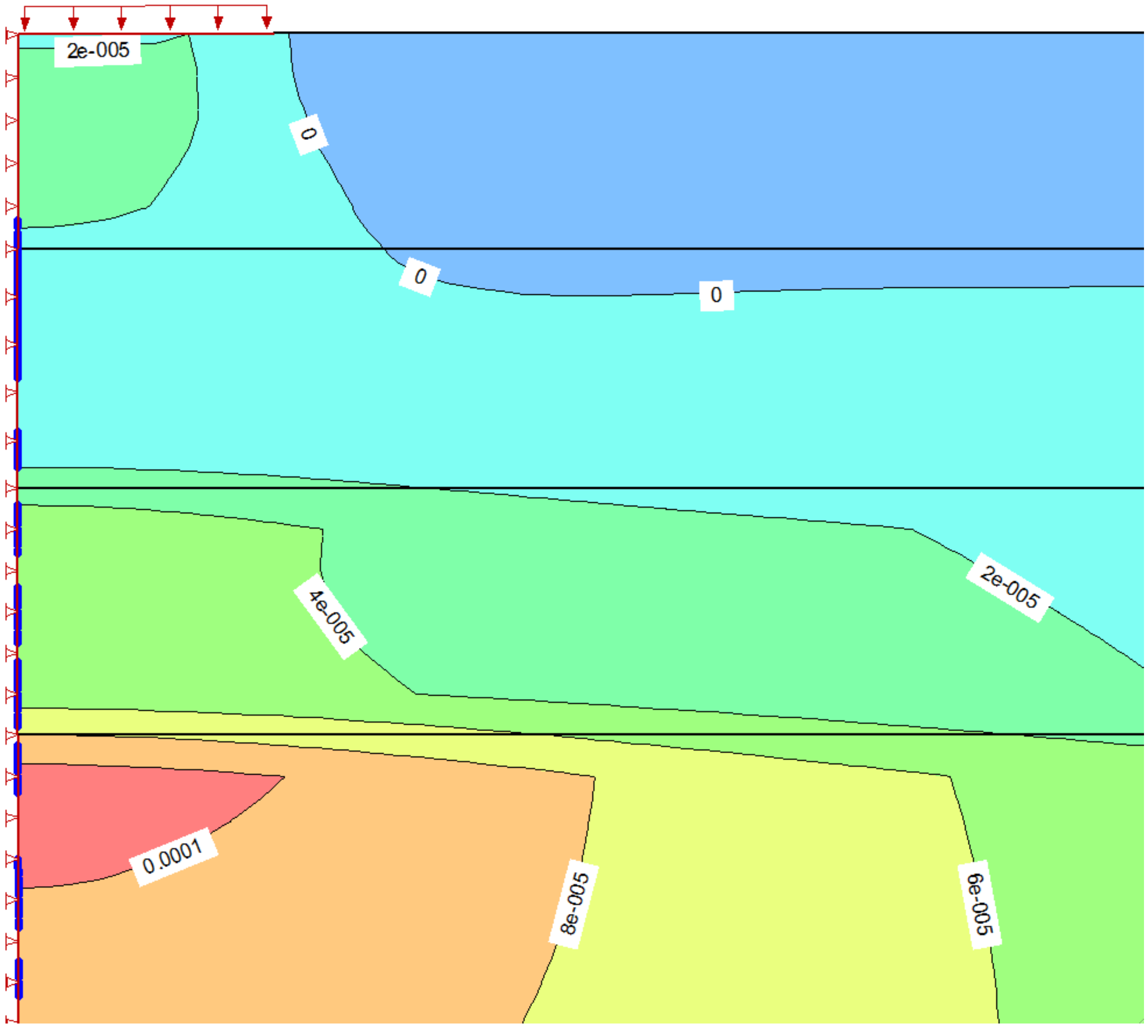
MODEL



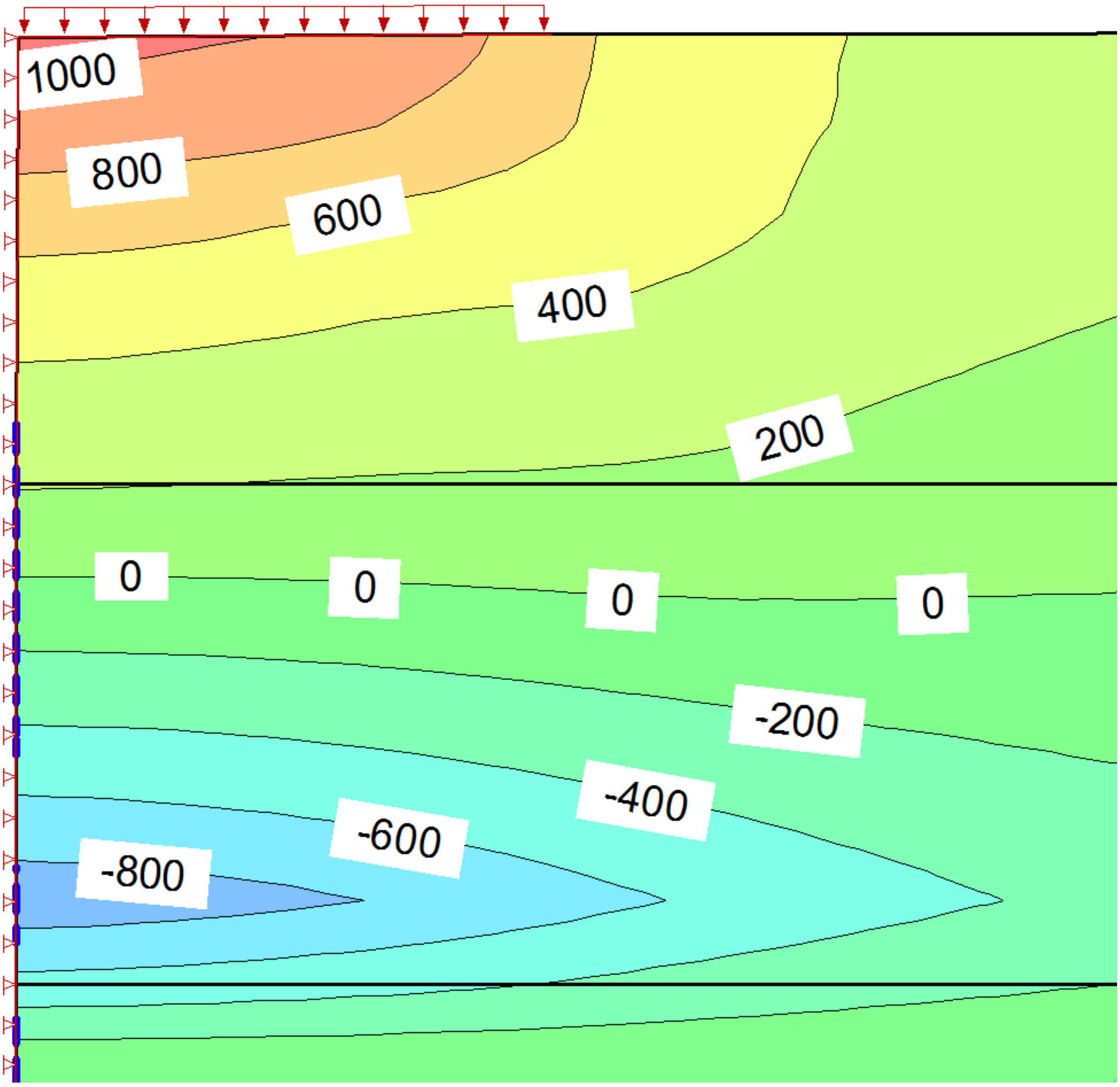
VERTICAL DEFLECTIONS



VERTICAL STRAINS

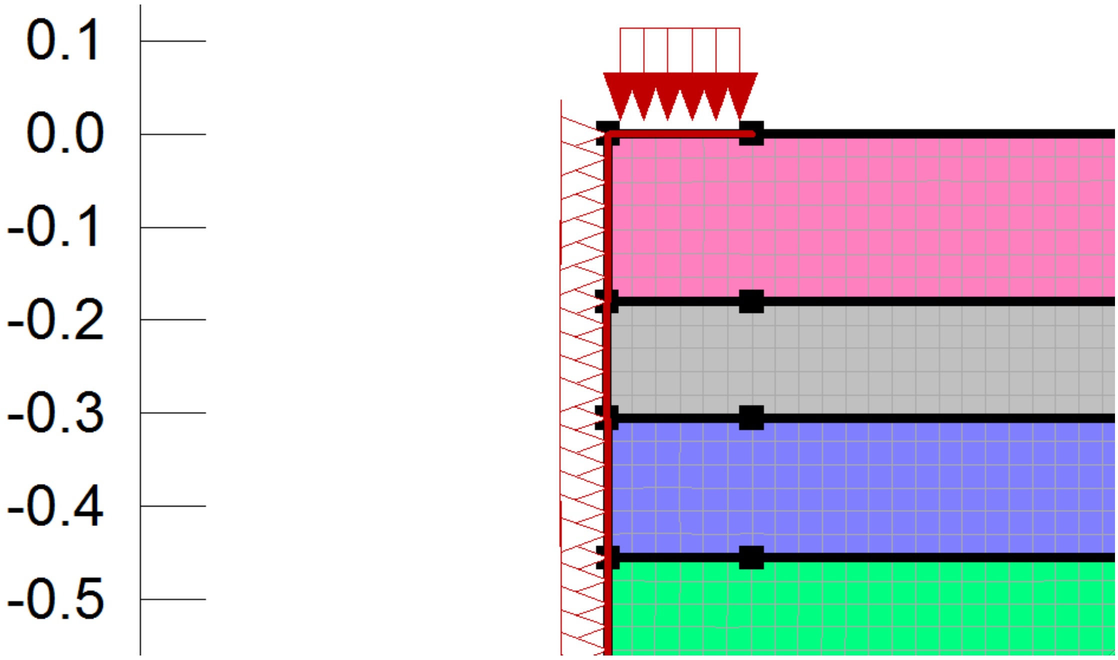


HORIZONTAL STRESSES

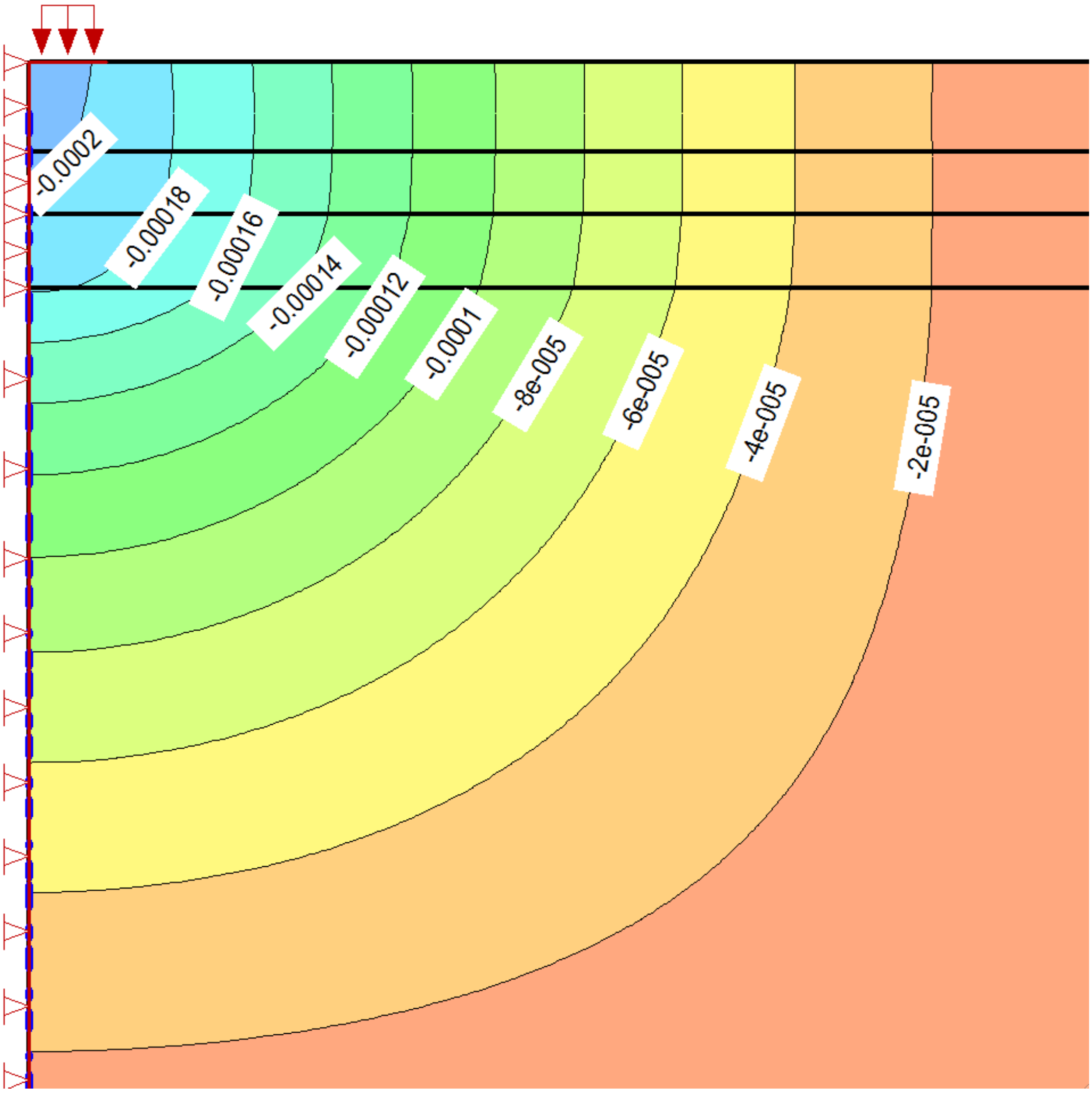


BOUND SURFACE RIGID BASE PIETRA PAVE PAVEMENTS 4MSA TO 8MSA

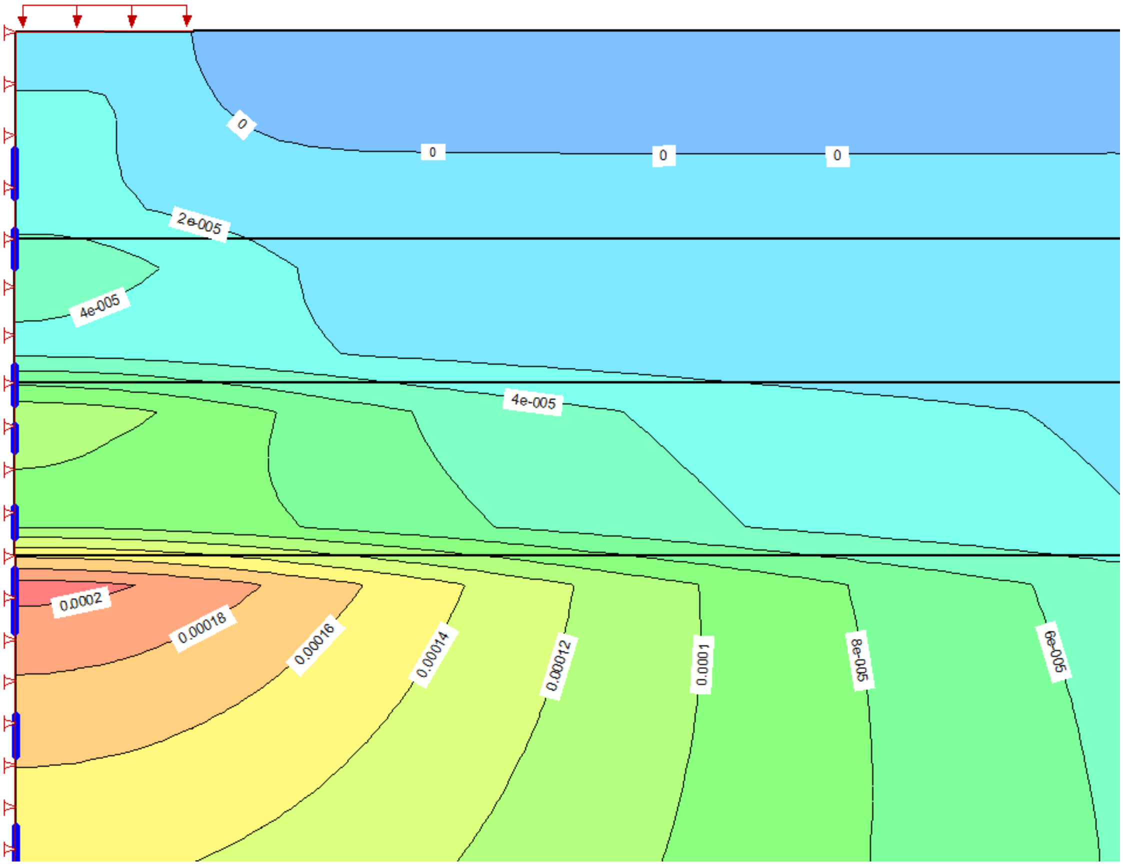
MODEL



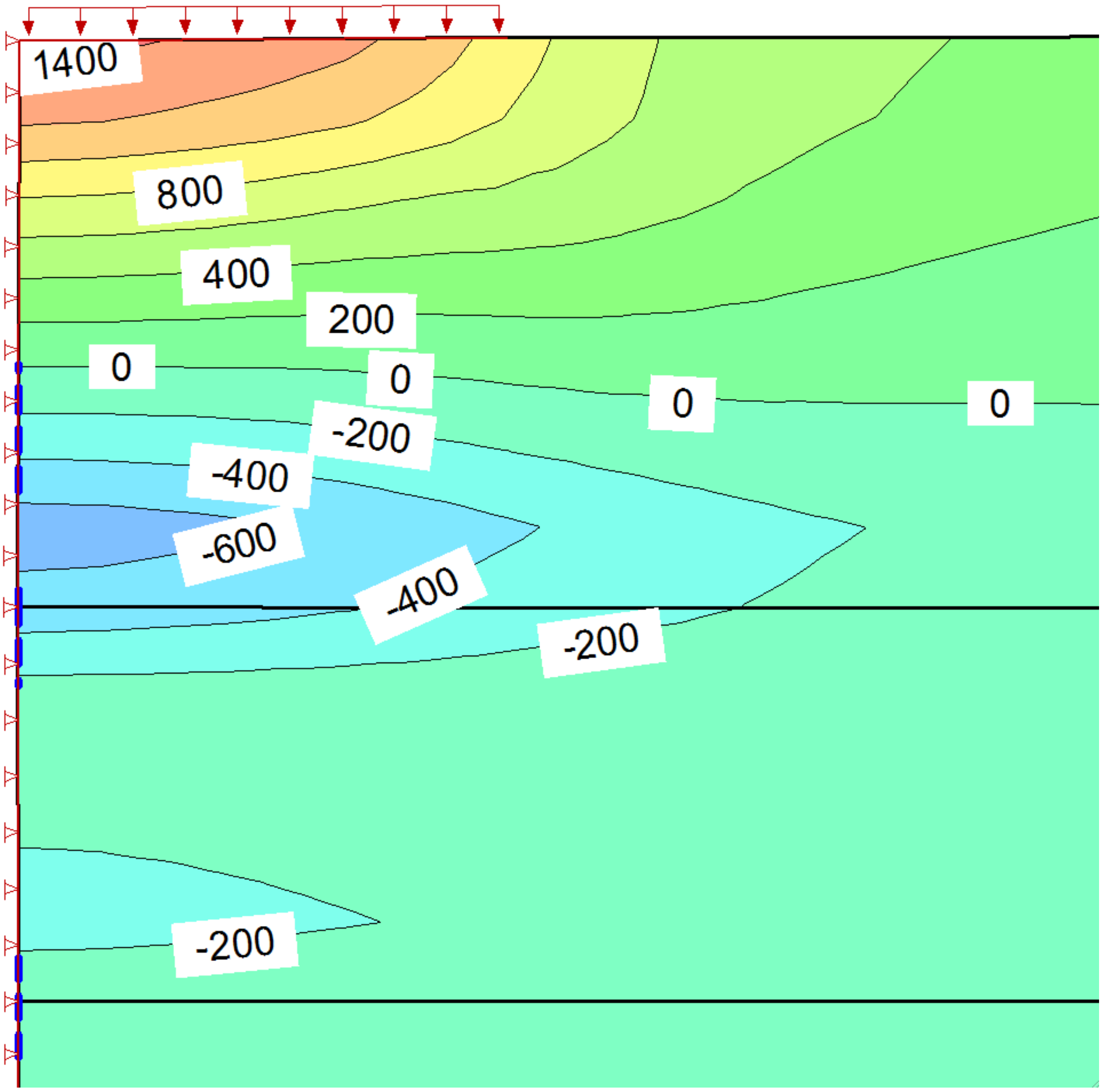
VERTICAL DEFLECTIONS



VERTICAL STRAINS

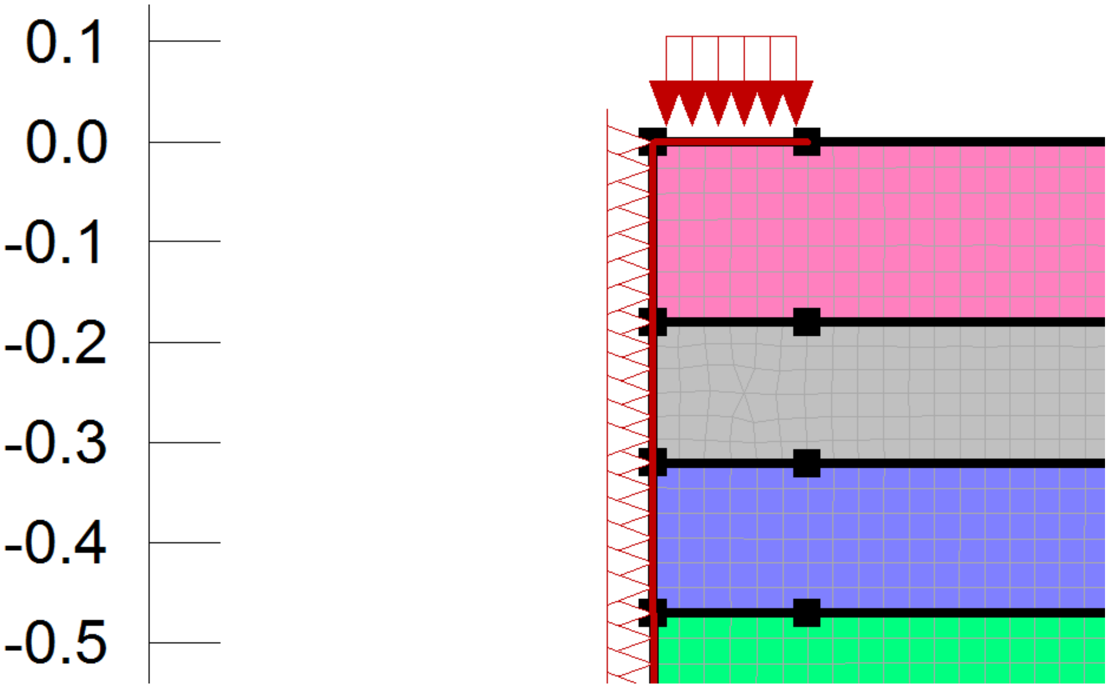


HORIZONTAL STRESSES

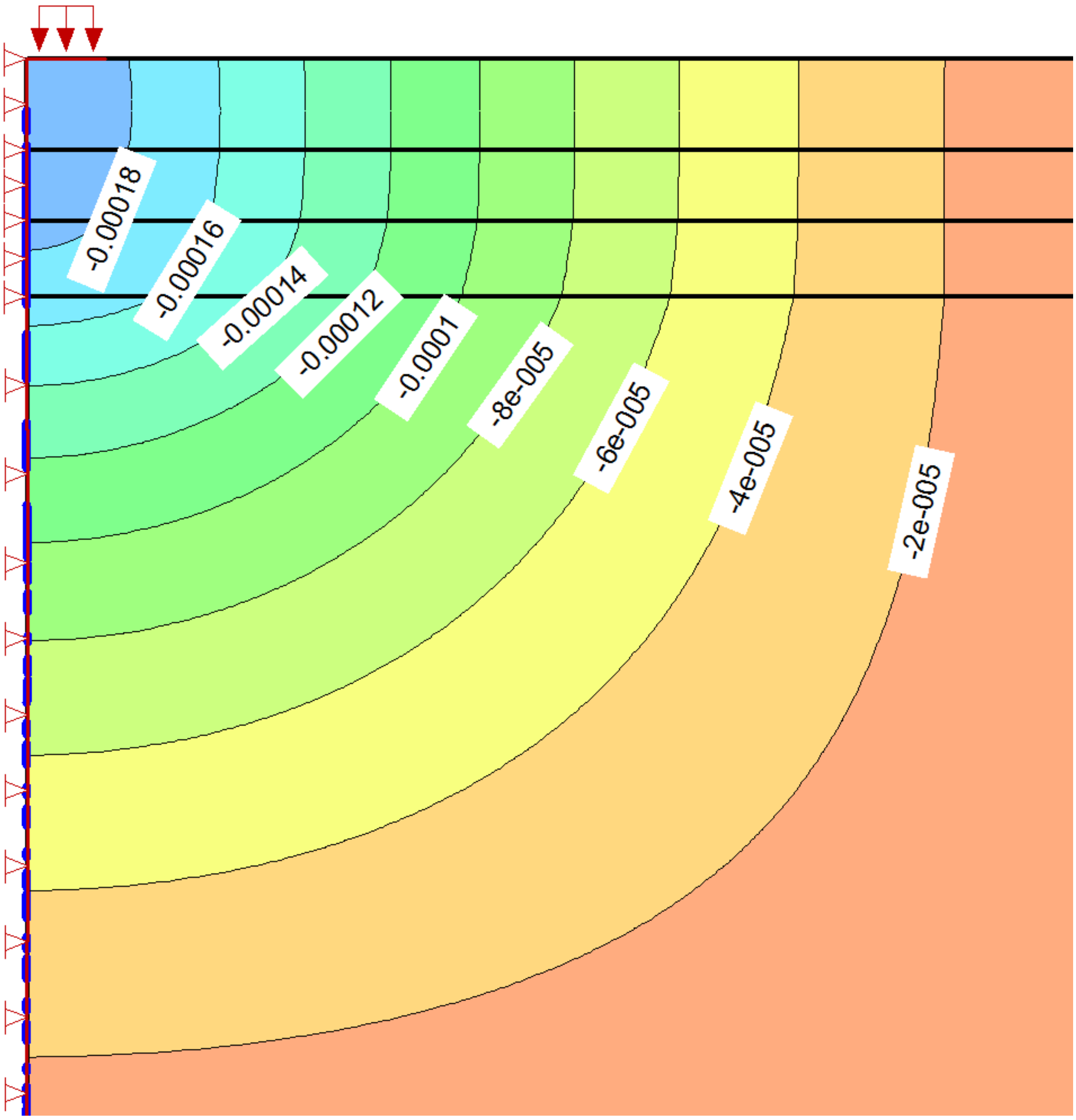


BOUND SURFACE RIGID BASE
PIETRA PAVE PAVEMENTS
8MSA TO 12MSA

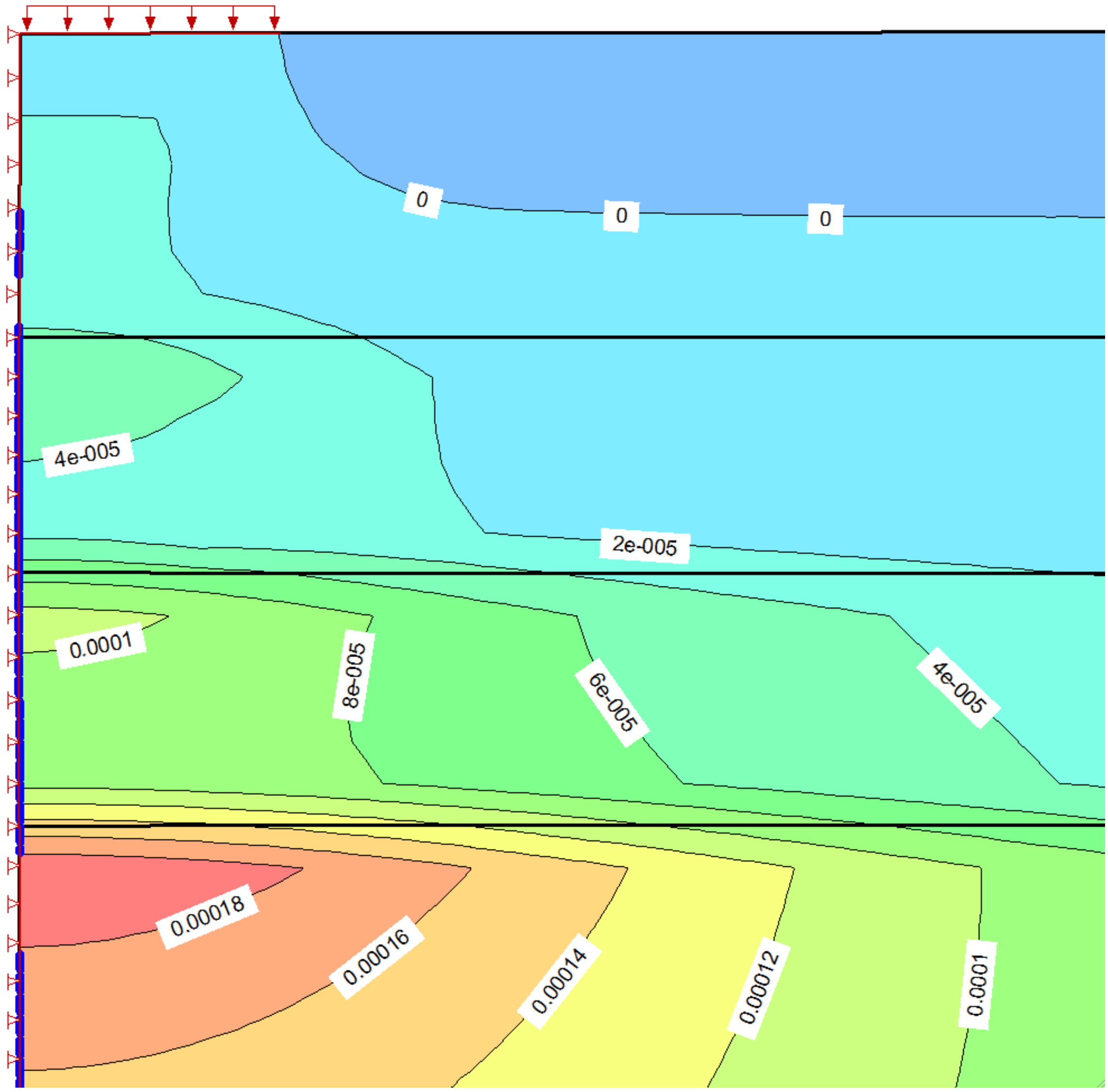
MODEL



VERTICAL DEFLECTIONS



VERTICAL STRAINS



HORIZONTAL STRESSES