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Seismic Safety Evaluation of Buried Pipelines

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Abstract:

The pipeline systems are commonly used to transport water, sewage, oil, natural gas and other materials world over. These pipelines run over long distances and in some instances they cross high seismic areas including fault crossings. These pipelines should be designed in such a way that they remain functional even when they are subjected to high intensity earthquake shaking. The present study illustrates the performance of one of the high pressure gas pipeline in the state of Gujarat, under Permanent Ground Displacement, Buoyancy due to liquefaction, fault movement and Seismic wave propagation for different soils. Variation of tension and compression strains with respect to different thicknesses and diameters of buried pipelines are discussed. Based on the result from the study some recommendations are made to minimize the effect of earthquake on the pipeline. Study shows that the burial depth of pipeline should be minimized in the fault zone in order to reduce soil restrain on the pipeline during fault movement.

Index terms: Pipelines, Permanent ground deformation, Buoyancy due to liquefaction, Fault movement, Seismic wave propagation, Earthquake Hazard

1. Introduction

Lifeline systems in the civil engineering context include those facilities that address societal needs of energy (electricity, gas, liquid fuel, steam, etc.), water (potable, sewage and solid waste, flood, etc.), transportation (highways, bridges, harbors, transit, etc.) and communications (telephone, telegraph, radio, television, telecommunication, mail, press, etc.).

The well being of a community requires that these lifeline systems continue to function even after damaging earthquakes. Pipelines carry materials essential to the functioning and support of day-to-day life and maintenance of property and hence are often referred to as “lifelines”. These are commonly used in industries, public supplies, and for transportation of oil, gas, water and many other fluids and goods. Among the pipelines, important pipelines are generally buried below ground for aesthetic, safety, economic and environmental reasons. Experiences from past earthquakes show that pipelines are highly vulnerable to earthquake shaking. Pipeline systems are generally spread over a large geographical region and encounter a wide variety of seismic hazards and soil conditions.

2. Design Case Study

From the paper: Rajaram Chenna, Srikanth Terala, Ajay Pratap Singh (2014) -Vulnerability Assessment of Buried Pipelines: A Case Study, following data is considered for the problem statement.

A buried pipeline is designed to carry natural gas at a pressure (P) of 9.3 MPa.The installation temperature and operating temperature of the pipeline are 30°C and 65°C respectively.

The pipe is of API X-60 grade with outer diameter (D) of 30″ (0.762m) and wall thickness (t) of 0.0064m. Poisson's ratio and coefficient of thermal expansion of the pipe material can be considered as 0.3 and 12×10-6 respectively. The pipeline as described is buried with a soil cover of H=1.5m
Site: Soil of Coefficient of cohesion (C) = 30 kPa, angle of friction (φ) = 32° and effective unit weight of 18 kN/m^3.
The pipeline is checked for

Case I: Permanent ground displacement (PGD)
The length and width of PGD zone is 120 m and 50 m respectively. The ground displacement (δ l and δt) due to liquefaction can be taken as 2m. Check the pipeline safety if it is oriented
i) parallel to the direction of ground movement and
ii) transverse to the direction of ground movement.

Case II: Buoyancy due to liquefaction
The pipe is expected to experience buoyancy force during liquefaction over a length of about 50 m. The unit weight of saturated soil at the site is 18 kN/m^3. Assume the water table to be 1 m below the surface layer.

Case III: Fault crossing
The pipeline crosses a normal slip fault with fault displacement of 1.5 m and a dip angle of 35°. The pipeline crosses the fault line at an angle of 40°. The source to site distance can be considered as 20km.

Case IV: Seismic wave propagation
The expected peak ground acceleration (PGA) in the site is 0.45g at the base rock layer.
Where: Case 1: Permanent ground displacement (PGD)
Case 2: Buoyancy due to liquefaction
Case 3: Fault crossing
Case 4: Seismic wave propagation

3. Results

Seismic safety evaluation is carried out for straight pipeline for four different conditions as Permanent Ground Deformation, Buoyancy due to liquefaction, fault crossing and seismic wave propagation.
Different conditions considered for Permanent Ground Deformation and Buoyancy due to liquefaction are shown in table 1

Table 1: Conditions adapted for PGD and Liquefaction

SL NO	PGD (m)	Liquefaction (m)
1	L = 80; W = 30	L_b = 30
2	L = 100; W = 40	L_b = 40
3	L = 120; W = 50	L_b = 50
4	L = 140; W = 60	L_b = 60

Different soils considered for evaluation based on cohesion and angle of internal friction are shown in table 2

Table 2: Different soils considered for evaluation

SL NO	Cohesion (C)	Angle of Internal friction (ϕ)
1	0	20
2	0	30
3	100	0
4	200	0
5	30	32
6	50	30
7	100	20

For each soil condition parametric studies are carried out for four different diameters with varying thicknesses
Diameters of pipeline (mm) considered are 305, 458, 610 and 762
Thicknesses of pipes (mm) considered are 6.4, 7.4, 8.4, 9.4, 10.4, 12.4, 14.4, 17.4 and 21.4

The allowable strain in tension for steel pipe is (clause 3.9) = 3 % = 0.03
The allowable strain in compression for steel pipe is (clause 3.9) = $\varepsilon_{cr-c} = 0.175\frac{t}{R}$

Table 3: Allowable strains for different pipe diameters

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.03	0.00730	0.03	0.00490	0.03	0.00367	0.03	0.00294
7.4	0.03	0.00850	0.03	0.00566	0.03	0.00425	0.03	0.00340
8.4	0.03	0.00965	0.03	0.00643	0.03	0.00482	0.03	0.00386
9.4	0.03	0.01070	0.03	0.00720	0.03	0.00540	0.03	0.00432
10.4	0.03	0.01190	0.03	0.00796	0.03	0.00597	0.03	0.00478
12.4	0.03	0.01423	0.03	0.00940	0.03	0.00712	0.03	0.00570
14.4	0.03	0.01654	0.03	0.01102	0.03	0.00827	0.03	0.00661
17.4	0.03	0.01900	0.03	0.01330	0.03	0.00999	0.03	0.00799
21.4	0.03	0.02400	0.03	0.01638	0.03	0.01229	0.03	0.00983

T= Tension; C= Compression

CASE I: Permanent Ground Deformation (PGD):
Length and width (in m) of PGD Zone: L = 80, W = 30

Table 4: Strains for soil C = 30 & ϕ = 32º with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.00394	0.00244	0.00571	0.00387	0.00747	**0.00530**	0.00923	**0.00673**
7.4	0.00390	0.00249	0.00564	0.00394	0.00738	**0.00539**	0.00912	**0.00685**
8.4	0.00387	0.00252	0.00559	0.00399	0.00731	**0.00546**	0.00903	**0.00693**
9.4	0.00384	0.00255	0.00555	0.00403	0.00726	**0.00551**	0.00897	**0.00699**
10.4	0.00382	0.00257	0.00551	0.00406	0.00721	0.00556	0.00891	**0.00705**
12.4	0.00378	0.00260	0.00557	0.00411	0.00715	0.00562	0.00883	**0.00713**
14.4	0.00376	0.00262	0.00543	0.00415	0.00710	0.00567	0.00877	**0.00719**
17.4	0.00373	0.00265	0.00539	0.00419	0.00705	0.00572	0.00871	0.00725
21.4	0.00371	0.00267	0.00536	0.00422	0.00700	0.00577	0.00865	0.00731

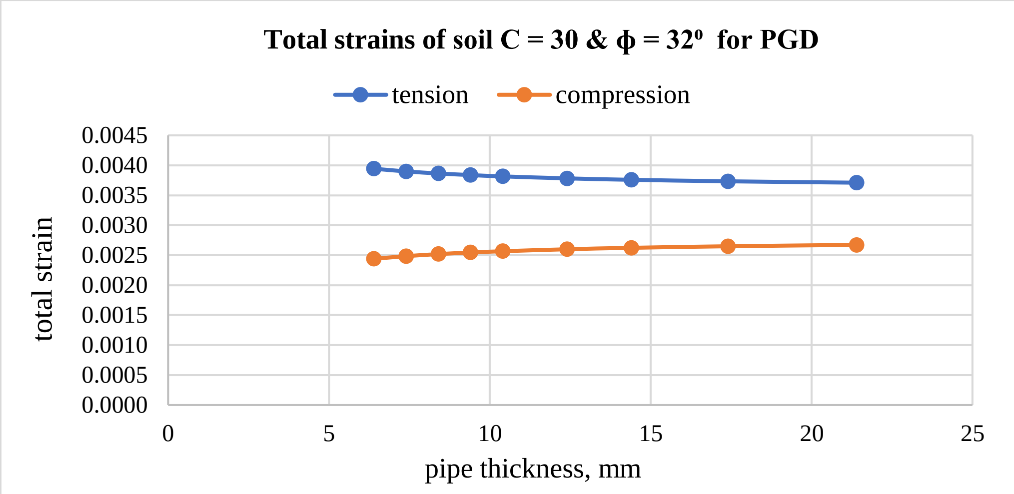

Fig 1: Typical graph of Maximum strains for 305 mm dia pipe of PGD 80m and 30m

CASE II: Buoyancy due to liquefaction:

Length of pipe in buoyancy zone (L_b) = 30m

Table 5 : Strains for soil C = 30 & ϕ = 32⁰ with different diameter pipes

Thickness (mm)	**305 mm dia**		**458 mm dia**		**610 mm dia**		**762 mm dia**	
	T	**C**	**T**	**C**	**T**	**C**	**T**	**C**
6.4	0.0016	0.0001	0.0019	0.0001	0.0022	0.0000	0.0024	-0.0001
7.4	0.0014	0.0000	0.0017	0.0000	0.0019	-0.0001	0.0021	-0.0002
8.4	0.0012	-0.0001	0.0015	-0.0001	0.0017	-0.0002	0.0019	-0.0002
9.4	0.0011	-0.0002	0.0013	-0.0002	0.0015	-0.0002	0.0017	-0.0003
10.4	0.0010	-0.0003	0.0012	-0.0002	0.0014	-0.0003	0.0015	-0.0003
12.4	0.0008	-0.0004	0.0011	-0.0003	0.0012	-0.0003	0.0013	-0.0004
14.4	0.0007	-0.0005	0.0009	-0.0004	0.0011	-0.0004	0.0012	-0.0004
17.4	0.0005	-0.0005	0.0008	-0.0004	0.0009	-0.0004	0.0010	-0.0004
21.4	0.0004	-0.0006	0.0006	-0.0005	0.0008	-0.0005	0.0009	-0.0005

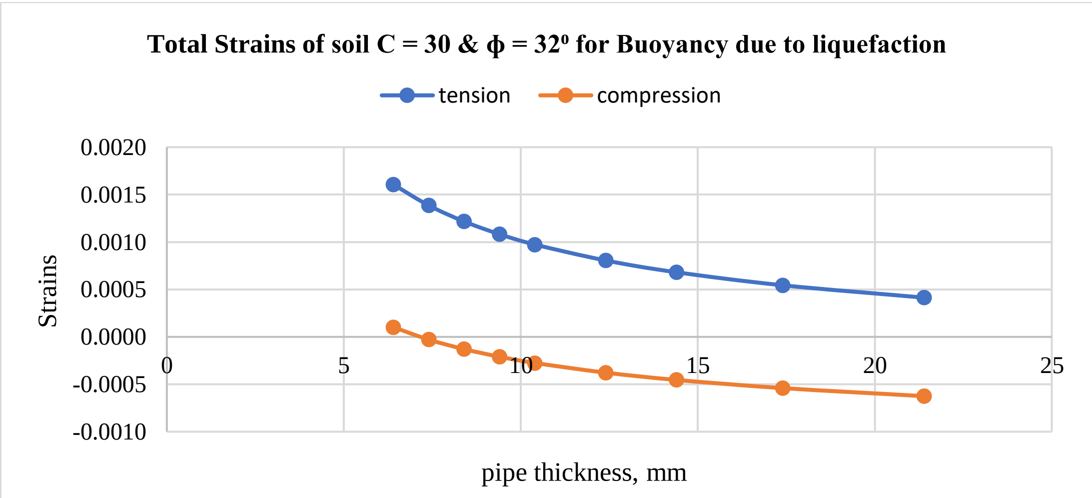

Fig 2: Typical graph of Maximum strains for 305 mm dia of soil C = 30 & ϕ = 32⁰

CASE III: Fault crossing:

For the expected normal slip fault displacement = δ_{fn} = 1.5m; β = 40°; Ψ = 35°

Table 6: Strains for soil C = 0 & ϕ = 20° with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.01597	**0.01447**	0.01614	**0.01430**	0.01630	**0.01414**	0.01647	**0.01397**
7.4	0.01593	**0.01451**	0.01607	**0.01437**	0.01621	**0.01422**	0.01636	**0.01408**
8.4	0.01589	**0.01455**	0.01602	**0.01442**	0.01615	**0.01429**	0.01627	**0.01417**
9.4	0.01587	**0.01457**	0.01598	**0.01446**	0.01609	**0.01435**	0.01620	**0.01423**
10.4	0.01584	**0.01459**	0.01595	**0.01449**	0.01605	**0.01439**	0.01615	**0.01429**
12.4	0.01581	**0.01463**	0.01590	**0.01454**	0.01598	**0.01446**	0.01607	**0.01437**
14.4	0.01579	0.01465	0.01586	**0.01458**	0.01593	**0.01450**	0.01601	**0.01443**
17.4	0.01576	0.01468	0.01582	**0.01462**	0.01588	**0.01456**	0.01594	**0.01449**
21.4	0.01574	0.01470	0.01579	0.01465	0.01584	**0.01460**	0.01589	**0.01455**

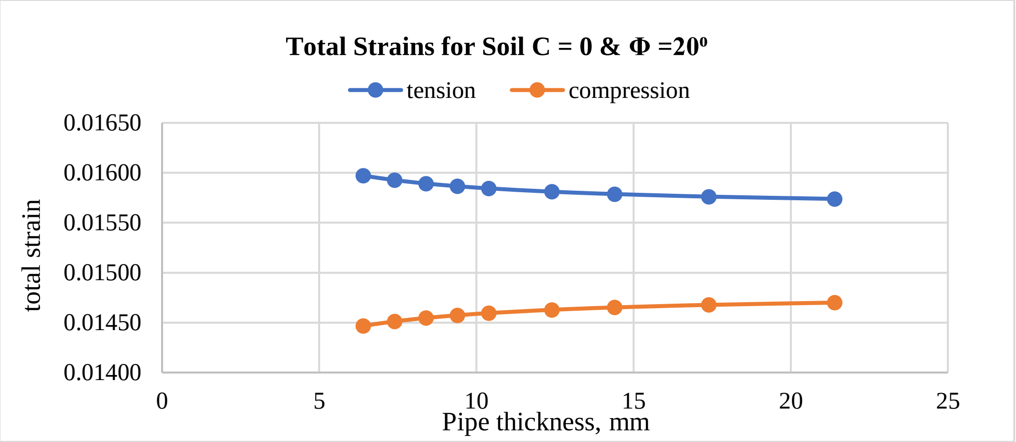

Fig 3: Typical graph of Maximum strains for 305 mm dia of soil C = 0 & ϕ = 20°

Table 7: Strains for soil C = 0 & ϕ = 30° with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.01597	**0.01447**	0.01614	**0.01430**	0.01630	**0.01414**	0.01647	**0.01397**
7.4	0.01593	**0.01451**	0.01607	**0.01437**	0.01621	**0.01422**	0.01636	**0.01408**
8.4	0.01589	**0.01455**	0.01602	**0.01442**	0.01615	**0.01429**	0.01627	**0.01417**
9.4	0.01587	**0.01457**	0.01598	**0.01446**	0.01609	**0.01435**	0.01620	**0.01423**
10.4	0.01584	**0.01459**	0.01595	**0.01449**	0.01605	**0.01439**	0.01615	**0.01429**
12.4	0.01581	**0.01463**	0.01590	**0.01454**	0.01598	**0.01446**	0.01607	**0.01437**
14.4	0.01579	0.01465	0.01586	**0.01458**	0.01593	**0.01450**	0.01601	**0.01443**
17.4	0.01576	0.01468	0.01582	**0.01462**	0.01588	**0.01456**	0.01594	**0.01449**
21.4	0.01574	0.01470	0.01579	0.01465	0.01584	**0.01460**	0.01589	**0.01455**

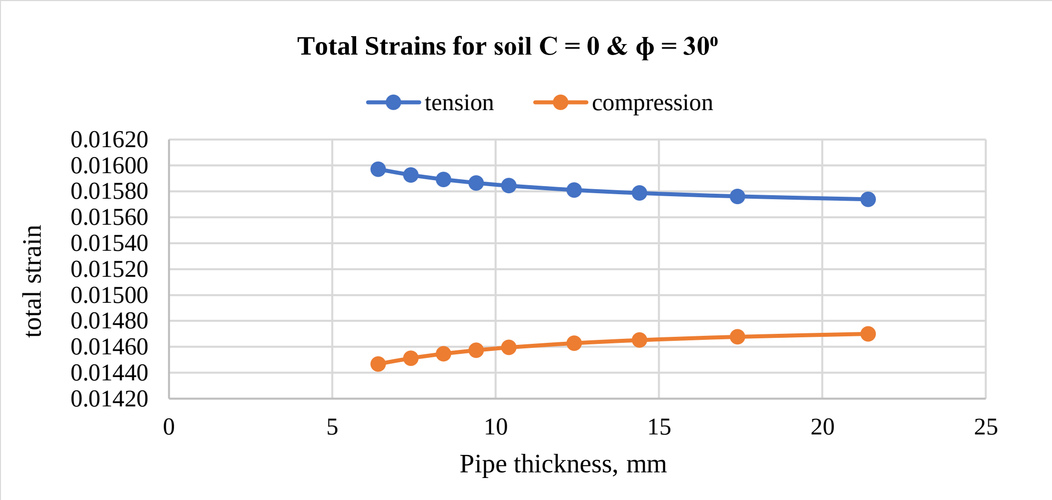

Fig 4: Typical graph of Maximum strains for 305 mm dia of soil C = 0 & $\phi = 30^0$

Table 8: Strains for soil C = 100 & $\phi = 0$ with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.05097	0.04947	0.05114	0.04930	0.05130	0.04913	0.05147	0.04897
7.4	0.04404	0.04262	0.04418	0.04248	0.04432	0.04234	0.04447	0.04219
8.4	0.03878	0.03743	0.03890	0.03730	0.03903	0.03718	0.03916	0.03705
9.4	0.03465	0.03336	0.03476	0.03324	0.03487	0.03313	0.03499	0.03302
10.4	0.03132	0.03007	0.03142	0.02997	0.03153	0.02987	0.03163	0.02977
12.4	0.02629	0.02511	0.02638	0.02503	0.02647	0.02494	0.02655	0.02485
14.4	0.02267	0.02154	0.02275	0.02146	0.02282	0.02139	0.02289	0.02132
17.4	0.01881	0.01773	0.01887	0.01767	0.01893	0.01761	0.01900	0.01754
21.4	0.01574	0.01470	0.01579	0.01465	0.01584	0.01460	0.01589	0.01455

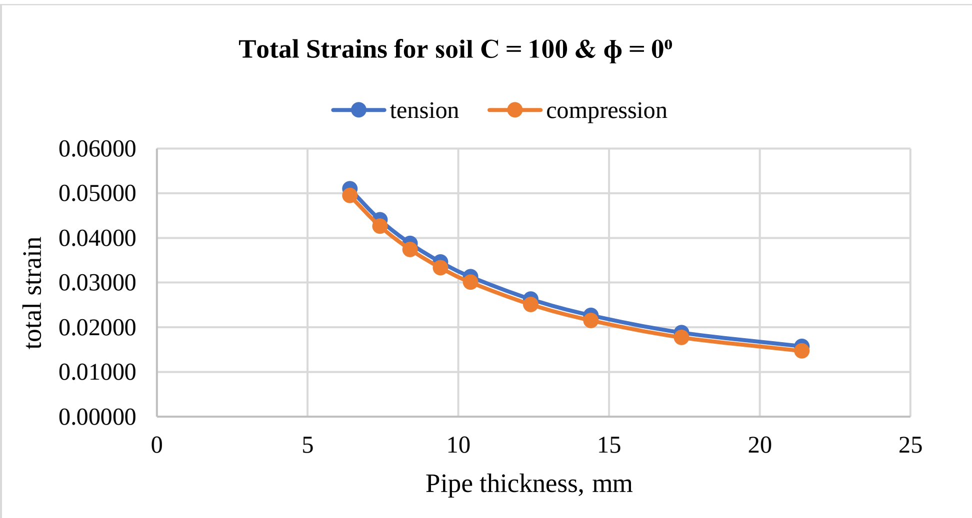

Fig 5: Typical graph of Maximum strains for 305 mm dia pipe of soil C = 100 & $\phi = 0^0$

Table 9: Strains for soil C = 200 & ϕ = 0 with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	**0.05637**	**0.05486**	**0.05653**	**0.05470**	**0.05670**	**0.05453**	**0.05686**	**0.05436**
7.4	**0.04868**	**0.04727**	**0.04883**	**0.04712**	**0.04897**	**0.04698**	**0.04911**	**0.04684**
8.4	**0.04285**	**0.04151**	**0.04298**	**0.04138**	**0.04311**	**0.04125**	**0.04323**	**0.04113**
9.4	**0.03828**	**0.03699**	**0.03839**	**0.03688**	**0.03851**	**0.03676**	**0.03862**	**0.03665**
10.4	**0.03460**	**0.03335**	**0.03470**	**0.03325**	**0.03480**	**0.03314**	**0.03490**	**0.03304**
12.4	**0.02903**	**0.02785**	**0.02912**	**0.02776**	**0.02920**	**0.02768**	**0.02929**	**0.02759**
14.4	0.02502	**0.02389**	0.02510	**0.02381**	0.02517	**0.02374**	0.02525	**0.02367**
17.4	0.02075	**0.01967**	0.02081	**0.01961**	0.02087	**0.01955**	0.02094	**0.01948**
21.4	0.01693	0.01589	0.01698	0.01584	0.01703	**0.01579**	0.01708	**0.01574**

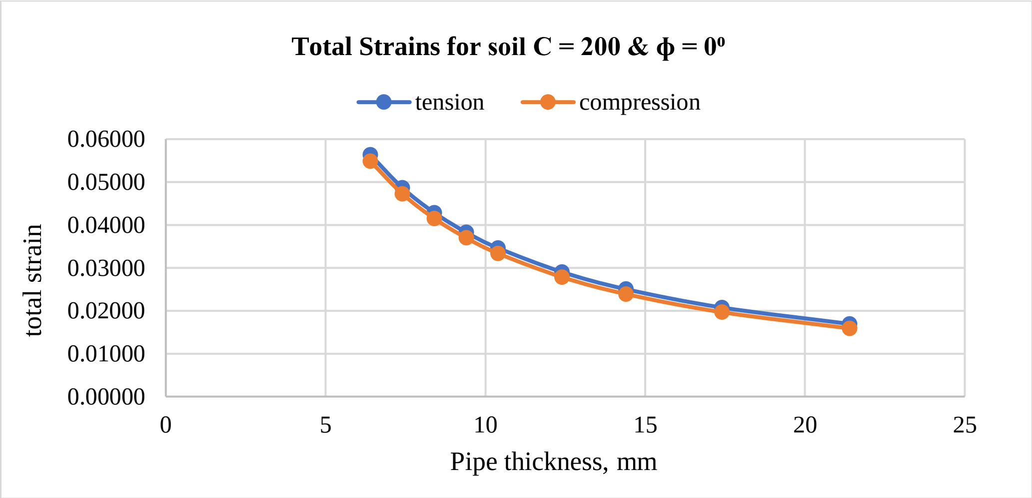

Fig 6: Typical graph of Maximum strains for 305 mm dia pipe of soil C = 200 & ϕ = 0°

Table 10: Strains for soil C = 30 & ϕ = 32° with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.02803	**0.02652**	0.02819	**0.02636**	0.02836	**0.02619**	0.02853	**0.02603**
7.4	0.02427	**0.02285**	0.02441	**0.02271**	0.02455	**0.02257**	0.02470	**0.02242**
8.4	0.02141	**0.02006**	0.02153	**0.01994**	0.02166	**0.01981**	0.02179	**0.01968**
9.4	0.01916	**0.01787**	0.01927	**0.01776**	0.01939	**0.01764**	0.01950	**0.01753**
10.4	0.01735	**0.01610**	0.01745	**0.01600**	0.01755	**0.01590**	0.01765	**0.01579**
12.4	0.01581	**0.01463**	0.01590	**0.01454**	0.01598	**0.01446**	0.01607	**0.01437**
14.4	0.01579	0.01465	0.01586	**0.01458**	0.01593	**0.01450**	0.01601	**0.01443**
17.4	0.01576	0.01468	0.01582	0.01462	0.01588	**0.01456**	0.01594	**0.01449**
21.4	0.01574	0.01470	0.01579	0.01465	0.01584	**0.01460**	0.01589	**0.01455**

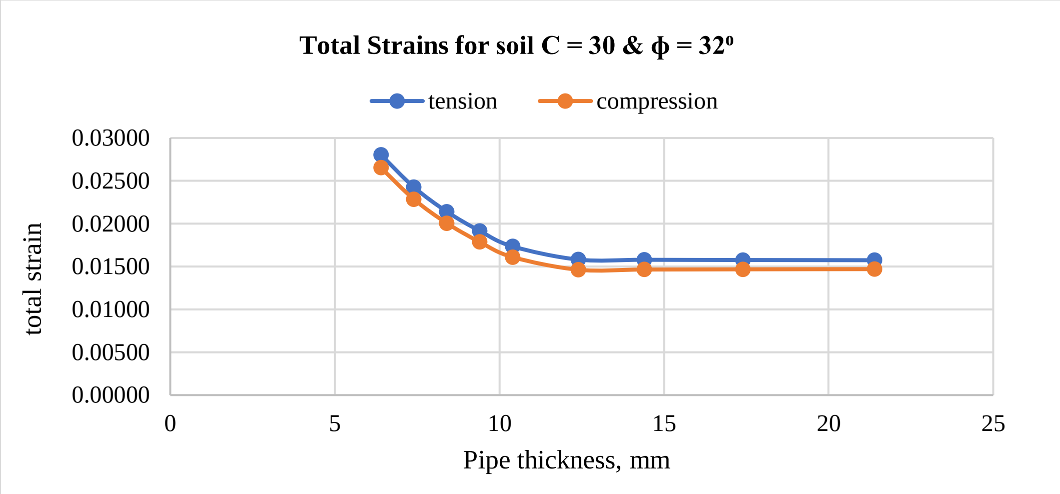

Fig 7: Typical graph of Maximum strains for 305 mm dia pipe of soil C = 30 & ϕ = 32⁰

Table 11: Strains for soil C = 50 & ϕ = 30⁰ with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	**0.04222**	**0.04071**	**0.04238**	**0.04054**	**0.04255**	**0.04038**	**0.04271**	**0.04021**
7.4	**0.03650**	**0.03508**	**0.03664**	**0.03494**	**0.03679**	**0.03480**	**0.03693**	**0.03465**
8.4	**0.03216**	**0.03081**	**0.03228**	**0.03068**	**0.03241**	**0.03056**	**0.03254**	**0.03043**
9.4	**0.02875**	**0.02746**	**0.02886**	**0.02734**	**0.02897**	**0.02723**	**0.02909**	**0.02712**
10.4	**0.02600**	**0.02475**	**0.02610**	**0.02465**	**0.02620**	**0.02455**	**0.02631**	**0.02444**
12.4	0.02184	**0.02066**	0.02193	**0.02057**	0.02201	**0.02049**	0.02210	**0.02040**
14.4	0.01885	**0.01771**	0.01892	**0.01764**	0.01900	**0.01757**	0.01907	**0.01749**
17.4	0.01576	0.01468	0.01582	**0.01462**	0.01588	**0.01456**	0.01594	**0.01449**
21.4	0.01574	0.01470	0.01579	0.01465	0.01584	**0.01460**	0.01589	**0.01455**

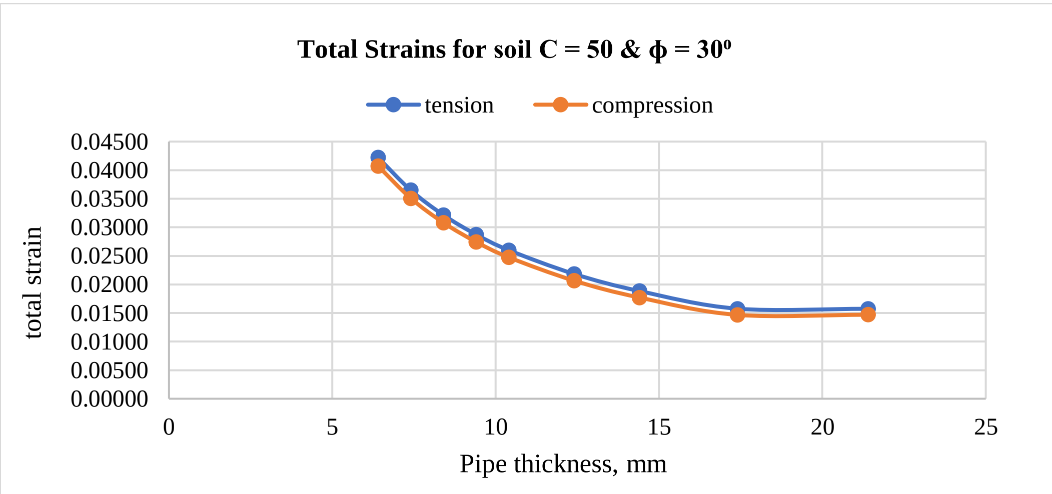

Fig 8: Typical graph of Maximum strains for 305 mm dia pipe of soil C = 50 & ϕ = 30⁰

Table 12: Strains for soil C = 100 & ϕ = 20⁰ with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	**0.05507**	**0.05357**	**0.05524**	**0.05340**	**0.05541**	**0.05324**	**0.05557**	**0.05307**
7.4	**0.04757**	**0.04616**	**0.04771**	**0.04601**	**0.04786**	**0.04587**	**0.04800**	**0.04572**
8.4	**0.04188**	**0.04053**	**0.04200**	**0.04041**	**0.04213**	**0.04028**	**0.04226**	**0.04015**
9.4	**0.03741**	**0.03612**	**0.03752**	**0.03601**	**0.03764**	**0.03589**	**0.03775**	**0.03578**
10.4	**0.03381**	**0.03257**	**0.03392**	**0.03246**	**0.03402**	**0.03236**	**0.03412**	**0.03226**
12.4	0.02838	**0.02719**	0.02846	**0.02711**	**0.02855**	**0.02702**	**0.02863**	**0.02694**
14.4	0.02446	**0.02333**	0.02454	**0.02325**	0.02461	**0.02318**	0.02468	**0.02310**
17.4	0.02029	**0.01920**	0.02035	**0.01914**	0.02041	**0.01908**	0.02047	**0.01902**
21.4	0.01655	0.01551	0.01660	0.01547	0.01665	**0.01542**	0.01670	**0.01537**

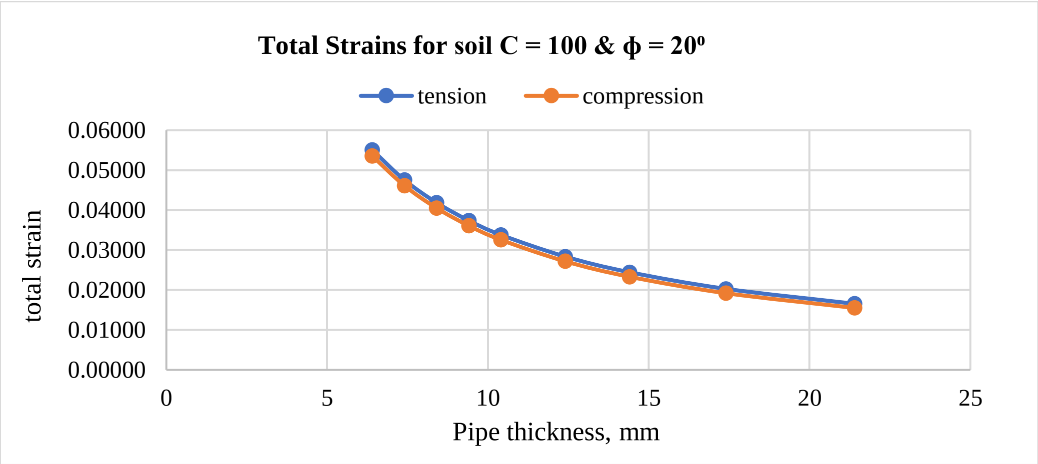

Fig 9: Typical graph of Maximum strains for 305 mm dia pipe of soil C = 100 & ϕ = 20⁰

CASE IV: Seismic wave propagation:
For the expected Peak Ground Acceleration of the site at base (PGA_r) = 0.45g

Table 13: Strains for soil site E (Soft soil) with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.0010	-0.0005	0.0011	-0.0007	0.0013	-0.0009	0.0015	-0.0010
7.4	0.0009	-0.0005	0.0011	-0.0006	0.0012	-0.0008	0.0014	-0.0009
8.4	0.0009	-0.0005	0.0010	-0.0006	0.0011	-0.0007	0.0013	-0.0008
9.4	0.0009	-0.0004	0.0010	-0.0005	0.0011	-0.0007	0.0012	-0.0008
10.4	0.0008	-0.0004	0.0009	-0.0005	0.0010	-0.0006	0.0011	-0.0007
12.4	0.0008	-0.0004	0.0009	-0.0005	0.0010	-0.0006	0.0011	-0.0006
14.4	0.0008	-0.0004	0.0009	-0.0004	0.0009	-0.0005	0.0010	-0.0006
17.4	0.0008	-0.0003	0.0008	-0.0004	0.0009	-0.0005	0.0009	-0.0005
21.4	0.0007	-0.0003	0.0008	-0.0004	0.0008	-0.0004	0.0009	-0.0005

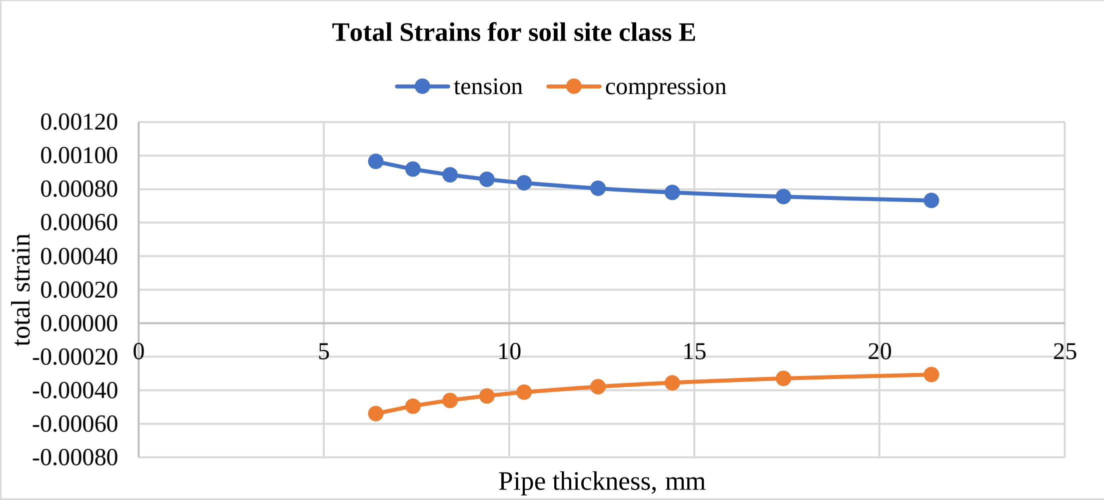

Fig 10: Typical graph of Maximum strains for 305 mm dia pipe of soil site E (Soft soil)

Table 14: Strains for soil site D (Stiff soil) with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.0009	-0.0006	0.0011	-0.0007	0.0013	-0.0009	0.0014	-0.0011
7.4	0.0009	-0.0005	0.0010	-0.0007	0.0012	-0.0008	0.0013	-0.0010
8.4	0.0008	-0.0005	0.0010	-0.0006	0.0011	-0.0008	0.0012	-0.0009
9.4	0.0008	-0.0005	0.0009	-0.0006	0.0010	-0.0007	0.0012	-0.0008
10.4	0.0008	-0.0004	0.0009	-0.0006	0.0010	-0.0007	0.0011	-0.0008
12.4	0.0008	-0.0004	0.0009	-0.0005	0.0009	-0.0006	0.0010	-0.0007
14.4	0.0007	-0.0004	0.0008	-0.0005	0.0009	-0.0005	0.0010	-0.0006
17.4	0.0007	-0.0004	0.0008	-0.0004	0.0008	-0.0005	0.0009	-0.0006
21.4	0.0007	-0.0003	0.0007	-0.0004	0.0008	-0.0004	0.0008	-0.0005

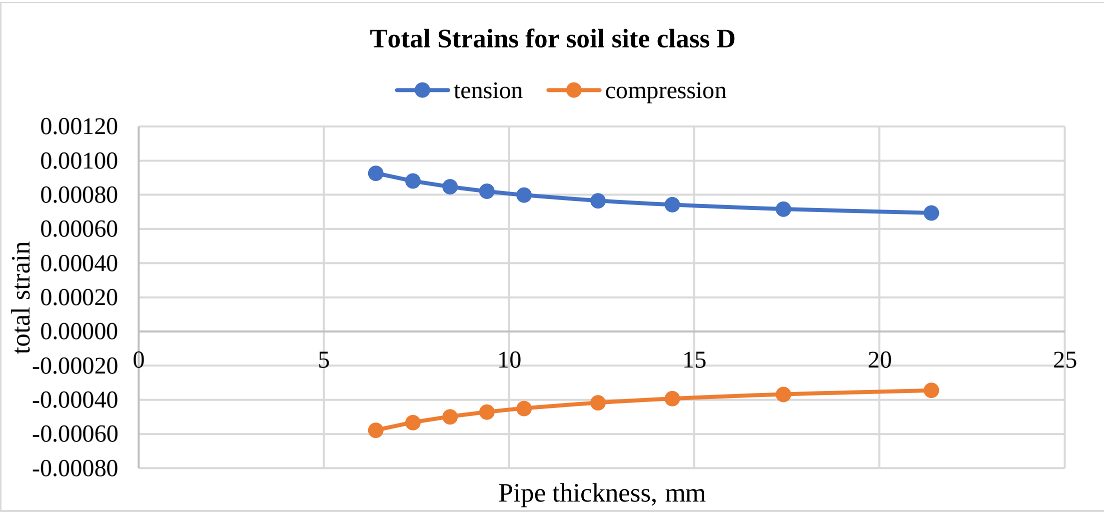

Fig 11: Typical graph of Maximum strains for 305 mm dia pipe of soil site D (Stiff soil)

Table 15: Strains for soil site C (Soft Rock) with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.0009	-0.0006	0.0010	-0.0008	0.0012	-0.0010	0.0014	-0.0011
7.4	0.0008	-0.0006	0.0010	-0.0007	0.0011	-0.0009	0.0012	-0.0010
8.4	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008	0.0012	-0.0009
9.4	0.0008	-0.0005	0.0009	-0.0006	0.0010	-0.0008	0.0011	-0.0009
10.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008
12.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0007
14.4	0.0007	-0.0005	0.0008	-0.0005	0.0008	-0.0006	0.0009	-0.0007
17.4	0.0007	-0.0004	0.0007	-0.0005	0.0008	-0.0006	0.0008	-0.0006
21.4	0.0006	-0.0004	0.0007	-0.0005	0.0007	-0.0005	0.0008	-0.0006

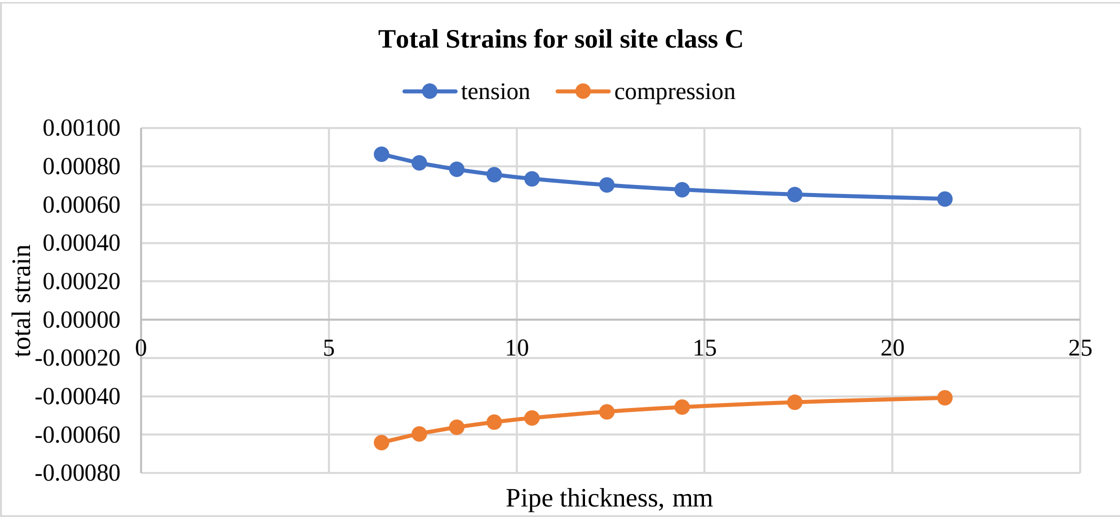

Fig 12: Typical graph of Maximum strains for 305 mm dia pipe of soil site C (Soft rock)

Table 16: Strains for soil site B (Rock) with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.0009	-0.0006	0.0010	-0.0008	0.0012	-0.0010	0.0014	-0.0011
7.4	0.0008	-0.0006	0.0010	-0.0007	0.0011	-0.0009	0.0012	-0.0010
8.4	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008	0.0012	-0.0009
9.4	0.0008	-0.0005	0.0009	-0.0006	0.0010	-0.0008	0.0011	-0.0009
10.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008
12.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0007
14.4	0.0007	-0.0005	0.0008	-0.0005	0.0008	-0.0006	0.0009	-0.0007
17.4	0.0007	-0.0004	0.0007	-0.0005	0.0008	-0.0006	0.0008	-0.0006
21.4	0.0006	-0.0004	0.0007	-0.0005	0.0007	-0.0005	0.0008	-0.0006

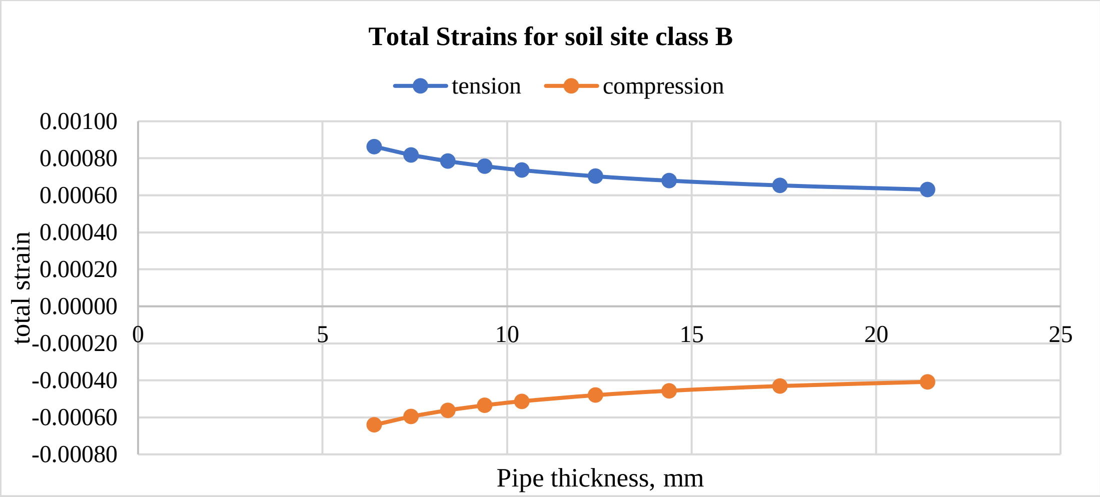

Fig 13: Typical graph of Maximum strains for 305 mm dia pipe of soil site class B (Rock)

Table 17: Strains for soil site A (Hard Rock) with different diameter pipes

Thickness (mm)	305 mm dia		458 mm dia		610 mm dia		762 mm dia	
	T	C	T	C	T	C	T	C
6.4	0.0008	-0.0007	0.0010	-0.0008	0.0012	-0.0010	0.0013	-0.0012
7.4	0.0008	-0.0006	0.0009	-0.0008	0.0011	-0.0009	0.0012	-0.0010
8.4	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008	0.0011	-0.0010
9.4	0.0007	-0.0006	0.0008	-0.0007	0.0010	-0.0008	0.0011	-0.0009
10.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0010	-0.0008
12.4	0.0007	-0.0005	0.0008	-0.0006	0.0009	-0.0007	0.0009	-0.0008
14.4	0.0007	-0.0005	0.0007	-0.0006	0.0008	-0.0006	0.0009	-0.0007
17.4	0.0006	-0.0005	0.0007	-0.0005	0.0008	-0.0006	0.0008	-0.0006
21.4	0.0006	-0.0004	0.0007	-0.0005	0.0007	-0.0005	0.0008	-0.0006

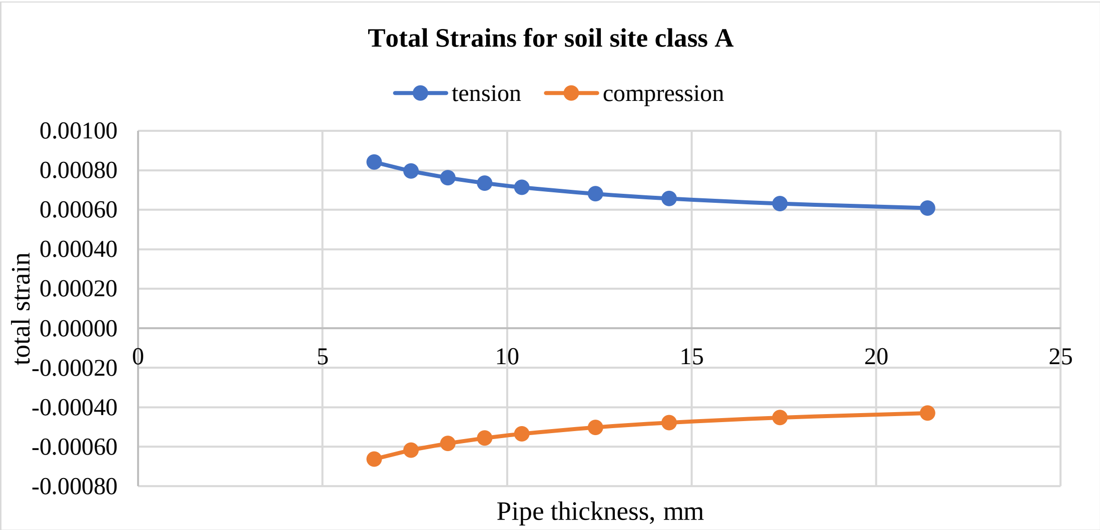

Fig 14: Typical graph of Maximum strains for 305 mm dia pipe of soil site class A (Hard rock)

4. Conclusions and Recommendations

Following are the major conclusions drawn from the results

1. From the results of PGD it is observed that with increase in pipe thickness strain in tension decreases where as strain in compression increases.
2. From the results of Buoyancy due to liquefaction it is observed that with increase in pipe thickness strain in tension and compression decreases.
3. From the results of Fault crossing it is observed that the curve variation is not same.
4. From the results of Seismic wave propagation it is observed that with increase in pipe thickness strain in tension decreases where as strain in compression increases.
5. In PGD, values of tension and compression strains remains constant, because strain calculations does not consider C and ϕ values in minimum value condition.
6. In Seismic wave propagation tension and compression strains are same and safe for all diameters and thicknesses.

In the design of a pipeline for crossing a fault line, the following considerations generally will improve the capability of the pipeline to withstand differential movement.

1. The pipelines crossing fault line should be oriented in such a way to avoid compression in the pipeline. The optimum angle of fault crossing will depend upon the dip of the fault plane and the expected type of movement. And it should be within 90º.
2. Pipeline ductility should be increased in fault-crossing region to accommodate large fault movement without rapture.
3. Abrupt changes in wall thickness should be avoided within fault zone.
4. In all areas of potential ground rapture, pipelines should be laid in relatively straight section avoiding sharp changes in direction and elevation.
5. To the extent possible, pipelines should be constructed without field bends, elbows, and flanges that tend to anchor the pipeline to the ground.
6. If longer length of pipeline is available then in the fault movement, level of strain gets reduced. Hence, the points of anchorage should be provided away from the fault zone to the extent possible in order to lower the level of strain in the pipeline.
7. The burial depth of pipeline should be minimized within fault zones in order to reduce soil restrain on the pipeline during fault movement

In the design of a pipeline for in the Liquefied zone, the following considerations generally will improve the capability of the pipeline to withstand buoyancy force due to soil liquefaction.

1. Concrete weights or gravel filled blankets can be utilized to provide additional resistance to buoyancy.
2. Buoyancy effect can also be minimized by shallow burial of the pipeline above the ground water level.
3. Where uplift is the main concern, one may provide anchors to prevent uplift.
4. An increase in pipe wall thickness will increase the pipeline’s capacity for buoyancy force due to soil liquefaction.
5. Use of shutoff valves may be increased to protect the pipeline of gas leakage in case of any severe damages.

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