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Laying Rigid Large Diameter Buried Pipelines: A Case Study of Different Approaches

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Abstract
Different methodologies are compared for constructing buried pipelines of different capacities and at different geotechnical conditions in the present study. From literature and provisions in codes, it was found that the cut and cover method of construction most suitable for buried pipelines with diameter less than 1 m in both flexible (steel or plastic) or rigid (concrete) pipeline material. From the study conducted, it was found that contemporary trenchless methods such as the New Austrian tunneling method use inclined and horizontal boring to carve an underground pipeline. Still, this method is financially viable only for large sections where pipeline length is large enough to justify the acquisition cost of TBMs and skilled labor. Trenchless methods can be used for any diameter size given adequate soil cover. This study shows that an external support structure, i.e., culvert, is required to lay small underground sections of pipelines of more than 2 m diameter to tolerate highway (freeway) loads. External support structure enveloping a pipeline buried under a road (freeway) or waterway is more economical, thus, avoiding deep excavations to achieve the depth of equal settlement. Soil cover equal to the depth of equal settlement is required to avoid and differential settlement in both cut and cover and trenchless method. A structurally designed culvert is employed for water transport pipelines running parallel to highways and buried under roads and waterways for small distances in this study. This mechanism was found to be better than employing TBM or the cut-and-cover method.

Introduction
Transportation using pipelines can be applied for water, gas, electricity (via wires) and public transport. These pipelines multifunctional pipelines are needed to be large in diameter to house such amenities with ease. Mostly, pipelines are buried to avoid vandalism and trespassing. The soil depth under which the pipe is buried should be adequate to disperse loads passed down from the ground surface.

With a diameter less than 2 m, smaller pipelines can be built underground with ease using trenchless and cut and cover methods nowadays. With a diameter of more than 2 m, large-diameter pipelines are required to be laid underground to carry something of that magnitude water supply to a city or subway. Thus, these large pipes are subjected to higher loads and require deep burial to disperse loads passed down from the ground surface. A soil cushion around the pipelines will be needed to be more than or equal to the depth of equal settlement. This depth of equal settlement is the height of the soil cover over the pipe to avoid any differential ground settlement due to stress projection to the ground surface. Soil cushion around the pipes can be of three categories; soil cover on top, soil cushion on the bottom, soil cover for the vertical trench wall. Their values can be determined by following provisions given in the design codes. This requires an elaborate design and one such project is presented here. This project describes a chain of three parallel running large diameter pipelines. The total length of each of the three pipelines will be approximately 62 km running parallel to the Kundli-Manesar-Palwal (KMP) Expressway in Delhi, India. While about 80% to 90% of the pipeline is expected to lie on sandy silt soil of alluvial origin, 10-20% of the total pipe length is expected to fall on rocky terrain. Except for some part of the pipe length (approximately 300 to 500 meters on each side of the open sewer drain), the groundwater table (GWT) is deep. The discharge will be carried by three pipelines running parallel to each other. The internal diameter of these pipelines will be 2 meters. The profile of the KMP expressway is such that the pumping for water in the pipe is mandatory. The type of pipe to be used is a prestressed cylindrical concrete pipe (PCCP). It is classified as a rigid pipe and the analysis is done using guidelines given in AWWA M9 (AWWA, 2008), ACPA (2000), IS 784 (2001) and IS 783 (1985).

Objective

This study will compare the design proposed by standard procedures and the suggested procedure for the project. The study will follow the guidelines given in AWWA M9 (AWWA, 2008), ACPA (2000), IS 784 (2001) and IS 783 (1985) to design soil cover around the pipe. A primary concern of this study is the part of the pipeline crossing, which will be under a highway, thus, subject to the live loads of the vehicles. Therefore, a culvert is designed to cover the pipeline while it lays in a highway underpass. In addition, finite element analysis is performed for the pipeline with and without a culvert to ensure safety in both methods.

Standard Design Procedure

The pipeline needs to be buried. Thus, the need for soil cover depth to dampen the settlement, cushion at the bottom to avoid hard surface contact and separation between two pipes, and separation from trench wall (side cushion) are needed to be defined. In addition, these params are designed for pipelines buried on the side of the road, thus, not facing any live loads.

Soil Cover

The absolute minimum depth of cover for a rigid concrete pipe is 0.9 m as given in AWWA M9 (AWWA, 2008), which is required to diffuse construction loads. Therefore, for the soil terrain where GWT is at a large depth, the minimum depth of cover 0.9 m is recommended. However, where the GWT is close to ground level, adequate depth of cover must be provided to safeguard against floatation. The worst condition for floatation is when the pipe is empty and the GWT is at ground level. For this case, the pipeline experiences a buoyant force counteracted by the pipe's self-weight and the weight of the soil wedge-formed, according to Whidden (2009). The calculations show that the recommended value of the factor of safety of 2 is obtained for the minimum depth of cover of 1.8 m. Hence, a minimum depth of cover of 1.8 m is recommended where the GWT is close to ground level. Furthermore, the minimum depth of cover in rocky and soft soil terrain, equal to 0.9 m, is recommended.

Minimum Spacing

Generally, in the design of minimum spacing between adjacent pipes, the structural strength of the pipe at the spring line must be greater than the vertical load. Therefore, failure (a performance limit) occurs if either of the following two occurs:

– Thrust in the pipe wall exceeds the ring compression strength.

– The vertical soil stress at the spring line exceeds the compressive strength (vertical passive resistance) of the soil.

However, in the present analysis, it is considered that no wheel load is present on the ground surface. Also, the pipes do not exert any lateral pressure on the soil at the spring line as the pipes are rigid and do not deflect under working conditions. Therefore, in this case, the minimum spacing is a problem of construction space requirement for safety and ease of operation'. Therefore, AWWA M9 (AWWA, 2008) recommends that to compact the backfill soil in the haunch area properly, the total width of the trench at crown line shall not be less than the pipe outside diameter plus 0.51 m. Based on this, a minimum clear spacing of 1.0 m between two parallel pipelines and 0.6 m between the pipe and the edge of the trench wall is recommended.

Type of Bedding and Design Load on the Pipelines (W_e)

The type of trench and bedding is specified based on IS 783 (1985), IS 3114 (1994) and AWWA M9 (AWWA, 2008). The trench type is wide trench as the cover depth to the trench width ratio is very low. The dead load due to backfill is calculated for positive projecting embankment (rigid pipe), as the trench width is high as given in IS 783 (1985). For a PCCP with external diameter greater than 1.83 m, R3-type bedding is recommended by AWWA M9 (AWWA, 2008), similar to the Class-C bedding given in IS 783 (1985). This bedding type applies to pipes laid on both earth as well as rocky terrains.

There are three zones or layers of the backfill, namely bedding (zone A), embedment or compacted fill (Zone B) and Ordinary fill (zone C), as shown in Fig. 1.

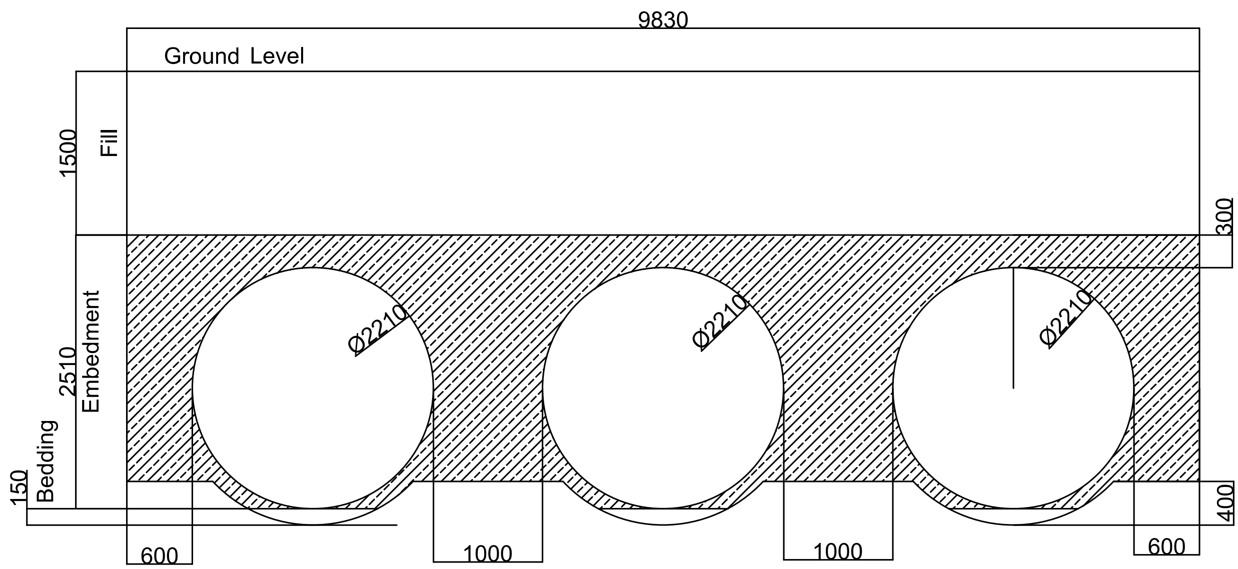

Fig. 1. Trench Specifications for pipelines under no vehicle load (all dimensions in mm)

All materials must satisfy the criteria given in IS 3114 (1994), which restricts using any material with cinders, gravel, boulders, rocks, slag ash, rubbish, vegetable, or any organic material for backfilling. Available soils and materials for the backfill are excavated material, Yamuna sand, and white dust. The excavated material is fine-grained soil (sandy silt with gravel); it cannot be used as a bedding or embedment (compacted fill). Yamuna sand satisfies all the specifications for embedment and backfill material and it is the major filling material to be used. However, for economic reasons, white dust with 30% fines can be mixed with Yamuna sand to obtain desired specifications for bedding or embedment fill.

For Ordinary backfill in zone C, excavated material, sandy silt with gravel, can be used if it satisfies all the criteria given in IS 3114 (1994). The gravel can be separated by screening and if the sandy silt is free from any deleterious material, it can be used as backfill material in zone C. The design test load is calculated by reducing the site loads by the bedding factor. The bedding factor depends on the quality of the bedding provided and the extent to which it holds and supports the pipe at a given location. The bedding factor applicable to the positive projecting wide trench was determined per IS 783 (1985). The projection ratio is calculated by dividing the vertical distance H between the top of the pipe and the level of the undisturbed ground surface on the sides of the pipes by the external diameter D of the pipe. For positive projecting wide trench condition (Rs = +1.0), projection ratio 0.9 and Class-C bedding, the terrain load factor of 2.8 is obtained corresponding to H/D ratio of 0.407 as per IS 783 (1985). Accordingly, the required minimum cracking load is 12.786 kN/m.

In the same way, the load factor and the required minimum cracking load for the soil terrain where the GWT is close to the ground surface are obtained as 2.44 and 30.976 kN/m. For pipelines buried under a drain, the mean scour depth is based on IRC 5 (IRC, 1998) and IRC 78 (IRC, 2014). Mean scour depth as a function of design discharge and silt factor. Soil cover to be provided will include scouring depth plus the depth of cover for which the resisting force is greater than the buoyant force with a factor of safety equal to 2.0, equal to 1.8 m. The external load (We) is calculated as per IS 784 (2001). The total cover required will be 1.06 (mean scour depth) + 1.80 = 2.86 m from the crown level of the pipe. Hence a cover of 2.86 m will be provided for pipeline crossing under the waterway. This will restrict the floatation of the pipeline in empty condition.

Design under Live Loads

As mentioned earlier, the pipeline will be crossing major highways, railway lines and waterways (canals, drains etc.). The guidelines for laying large diameter pipelines will cause the soil cover to increase approximately three times due to t the inclusion of impact loads passed on by highway. Codes referred for calculating the design load are IRC 6 (IRC, 2004) and IRC 21 (IRC, 2000). For live load consideration, Class AA loading with 70R tracked vehicle is considered. Two load cases are considered one-tracked (lane) and two-tracked (lane) vehicles. Load dispersion based on IRC 21 (IRC, 2000) at 45 degrees both along and across the span. A maximum of 100 kPa pseudo-static load will be applicable at the top of the highway. This load will be added to design the extra soil cover needed, which comes out to be more than 6 m from the top of the crown. This would be uneconomical to entrench a 2 m rigid PCCP with 6 m soil cover. The cushion from the side of the trench and bottom cushion will not change that much. As an alternative, a box culvert will be designed for carrying the pipeline inside to cross the highways and open drains safely. All three pipelines will require a box culvert to cover themselves, which is the basis of this design procedure. Reinforcement for slab design can be obtained by following the general guidelines of IS 456 (2000). The top and bottom slabs should

be designed as tension members. Sidewalls of the culvert can be designed as tension members if only inward bending of walls is considered. In this case, the inward bending of walls is considered. The top slab will carry pavement overburden and live loads of vehicle class 70(R) T dispersed over its span. Following are the points and details involved in calculations for overall load intensity.

1. Weight of pavement and soil cover = Σ (thickness of layer × unit weight of layer)
2. Live load = Wheel Force/ (dispersion length along span × dispersion length across span)
3. Dispersion length along span = vehicle length + 2 × (thickness of pavement + soil cover + slab thickness)
4. Dispersion length across span = Tire width + 2 × (thickness of pavement + soil cover)
5. Live load after impact factor = 1.25 X calculated live load
6. For two tracked vehicle loading, a reduction of 20% in wheel load is considered.

Moment calculation is based on the moment distribution method. Braking force is based on the force caused by the braking action of a vehicle. The braking force of the vehicle is taken from IRC 6 (IRC, 2004), equal to 20% of wheel load. This braking force will cause a braking moment that will be equally divided on each end. End moments are the summation of the distributed braking moment and distributed end moments. IS 456 (2000) is referred for limit state design purpose. Distribution reinforcement required is 0.12% of the cross-sectional area for any slab. Therefore, there is a need for 10 mm diameter bar reinforcement Fe415 rebars with 45 mm spacing in primary reinforcement and 215 mm spacing in tie reinforcement. Shear stress on all members is calculated and compared with design shear strength. Design shear strength can be calculated as a percentage reinforcement and concrete grade function from IRC 21 (IRC, 2000). All the members are safe with provided reinforcement. Various American agencies such as the Florida Department of Transportation (FDOT, 2012) and the Minnesota Department of Transportation prefer a minimum of 8-inch wall thickness with a 2-inch cover on both sides. In this design procedure, a 300 mm total wall/slab thickness is assumed to be on the safe side. This also works well with a 50 mm clear cover on both sides.

Corroboration by Finite Element Analysis

The design params calculated based on the standard procedure are validated with finite element analysis in ABAQUS. Dynamic/explicit integration is used as the soil is cohesionless; thus, it might cause divergence in the implicit integration scheme. All the surfaces are in contact with each other allowing for zero slip and zero separation conditions. Vertical boundaries are applied with roller boundaries and the bottommost boundary is fixed (encastre). Gravity load in

Addition with a surface load of 100kPa is applied at the top surface.

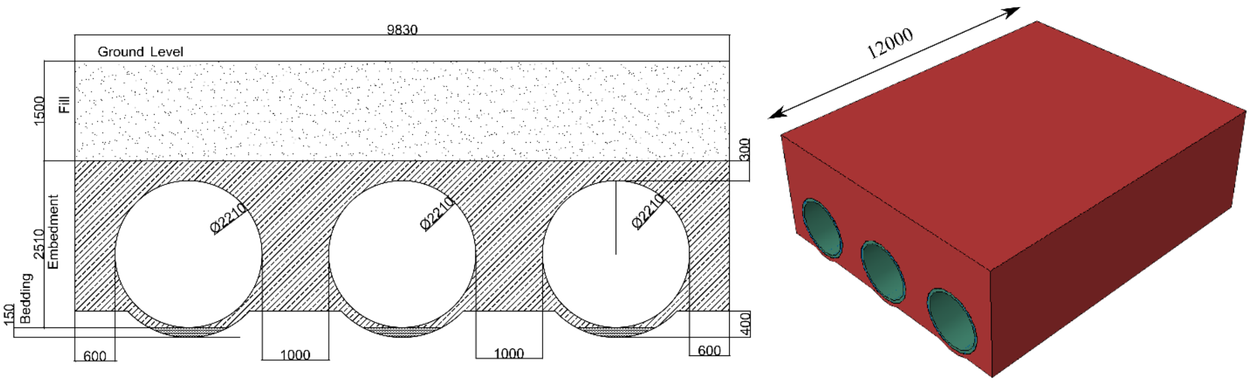

Fig. 2. ABAQUS model of the pipeline (all dimensions are in mm)

The design of the pipe is based on IS 784 (2001) and the design of the culvert is based on IS 456 (2000), IRC 6 (IRC, 2004) and IRC 21 (IRC, 2000), as shown in the previous section. The geometrical and modeling specifications are shown in Fig. 2, Fig. 3, Fig. 4, and Fig. 5. Soil cushion around the pipe is assumed to be uniform and made up of a mix of Yamuna sand and rock dust, whose Young's modulus and Poisson's ratio are 50 MPa and 0.45. Mohr-Coulomb failure params, cohesion and angle of internal friction are taken as 100Pa and 35 degrees. Properties of reinforcement steel and concrete are based on IS 456 (2000). Steel is assumed to be elastoplastic and a concrete damaged plasticity model is used for concrete.

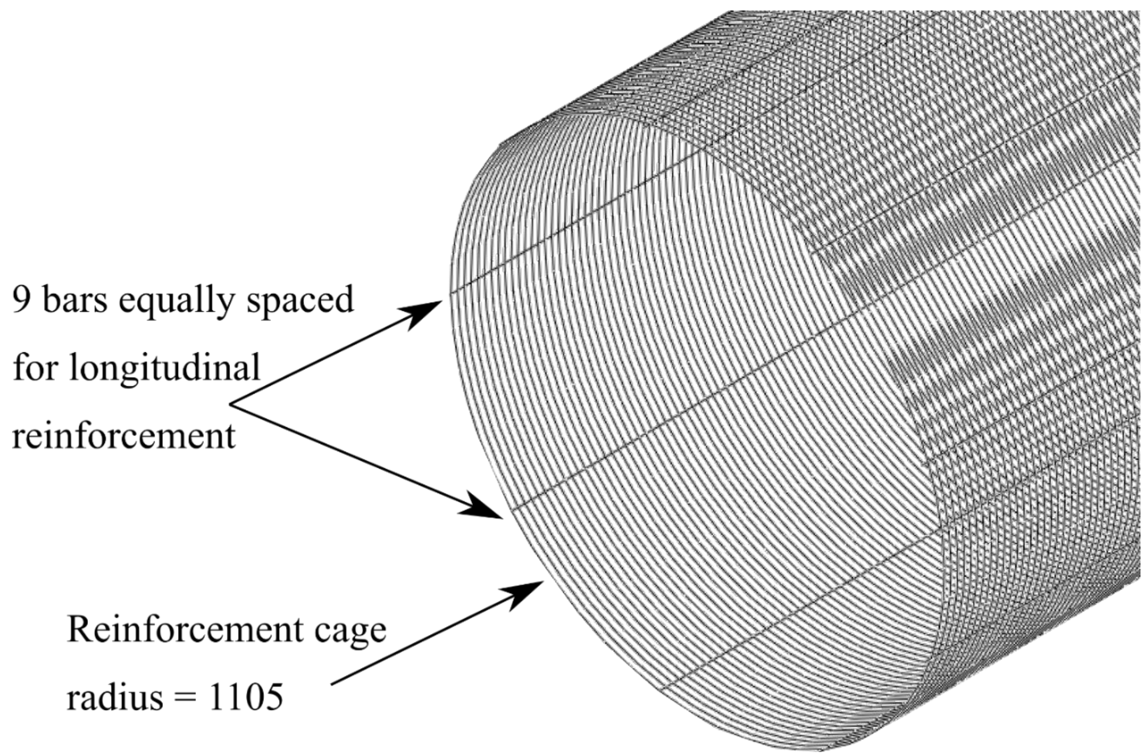

Fig. 3. ABAQUS model of the pipeline reinforcement cage (all dimensions are in mm)

Conclusions

The design of buried rigid pipelines based on specified guidelines is a matter of economy and structural integrity. A deep soil cover with trenchless method is the best economically viable solution available but only if the length of pipeline to be laid is more significant than 1 km. The cut and cover method will require deep trenching for the pipeline under live load. This will cost higher as compared to trenchless boring. A shallow culvert to pass a pipeline under live load will be the best solution. This will be cheaper than other methods. Indian Railways (RDSO, 2009) suggest a separate bridge for carrying a large diameter pipeline that crosses a rail track. Covering a pipeline with a culvert will also be a countermeasure to this problem.

Fig. 6 shows the vertical displacement contours in the culvert and pipelines due to dead and live loads. The maximum vertical deformation is in the pipes with 6 m soil cover on the top. Culvert, on the other hand, shows the least deformation of all cases. Therefore, it can be inferred that the maximum deformation in the culvert is significantly lower than in buried pipes; thus, pipes can be encased in culverts to avoid a large soil cover and make the design safer.

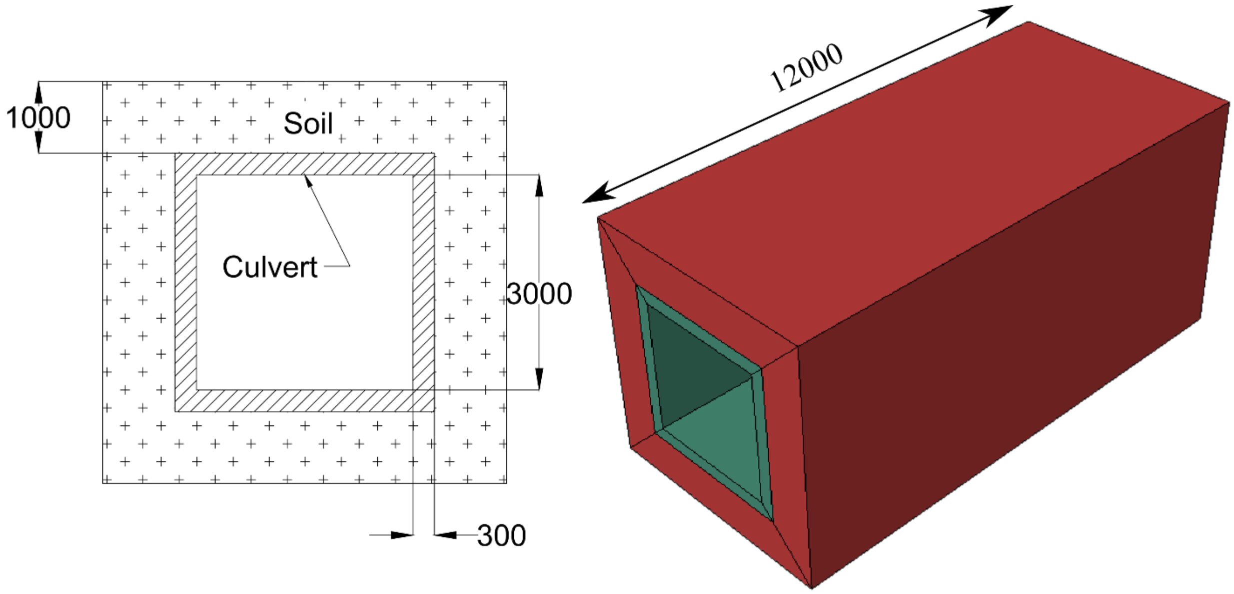

Fig. 4. ABAQUS model of the culvert (all dimensions are in mm)

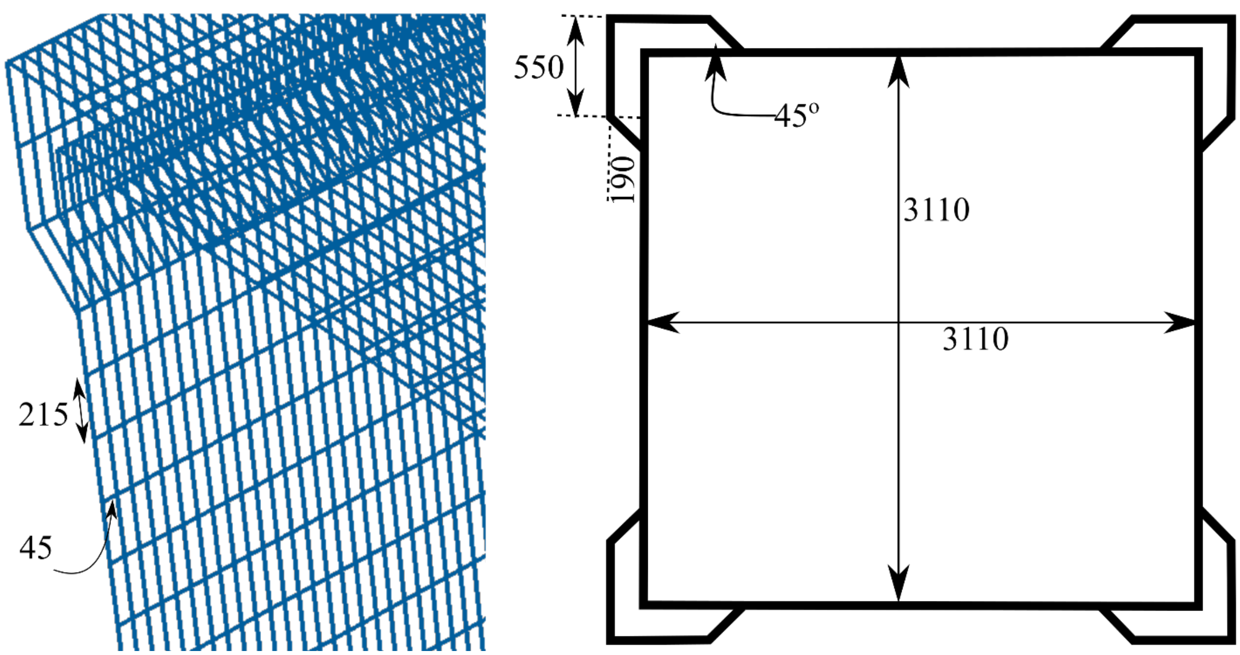

Fig. 5. ABAQUS model of the culvert reinforcement cage (all dimensions are in mm)

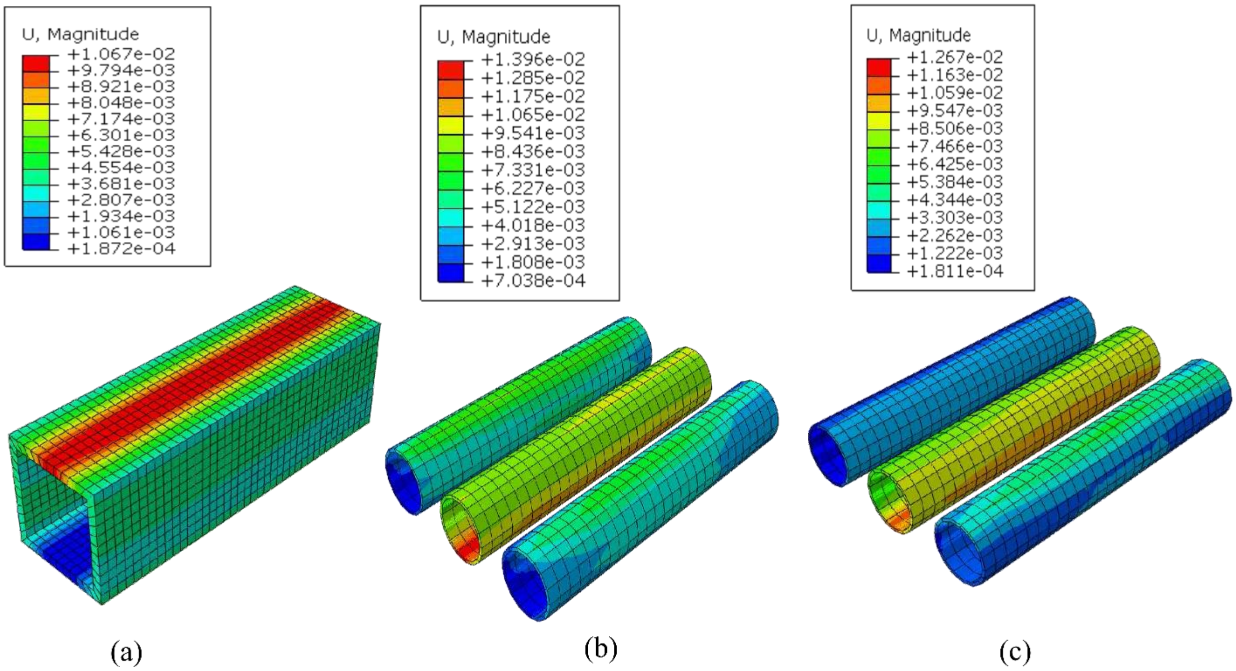

Fig. 6. Displacement contours in meters of (a) Culvert (b) Pipes with 6 m soil cover (c) pipes with 1.8 m soil cover

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