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Geotechnical perspectives of Failure cases in Head walls of Hume pipe culverts and their Forensic Investigations

Amit Srivastava[1] and Dharmendra Kumar Srivastava[2]

[1]Associate Professor, Department of Civil & Environmental Engineering, The NorthCap University, Gurgaon, Haryana – 122017. Email: amitsrivastava@ncuindia.edu
[2]Research Scholar, Department of Civil & Environmental Engineering, The NorthCap University, Gurgaon, Haryana – 122017. Email: srivastava.dk2009@gmail.com

Abstract:
The present study discuss and highlights the geotechnical aspects of failure cases observed in the head wall of Hume pipe culverts constructed at various locations on a bypass as apart work of ''Four Laning & strengthening of a national highway in Haryana state''. Systematic Forensic investigation of the observed cracks developed in a head wall of Hume pipe culvert suggested construction as well as design deficiencies. From geotechnical perspectives, various aspects of failure, such as, suitability of soil as foundation material, inadequate compaction of the foundation soil, consolidation process and amount of settlement etc. were studied. Observed performance and development of crack at the location of stress concentration in the head wall were also verified through numerical analysis using finite element based numerical tool PLAXIS 2D. Upon investigation, it has been found that inadequate compaction of soil below headwall foundation was the primary reason for excessive settlement and development of stress (tension) concentration at the top of the Hume pipe culvert that finally lead to the development of cracks. Also, the construction of the head wall was taken in a hasty manner and not much enough time was given for the PCC layer to stabilize and gain strength through enough curing. Apart from that the PCC layer below the headwall was missing and head wall was directly laid on the unprepared ground.

Keywords: *Forensic, Geotechnical, numerical, compaction, consolidation, construction*

Introduction

Forensic Geotechnical Engineering is a process which involves engineering, legal and scientific investigations and methods to detect the reasons of failure and process of development of sign of distress, failure and collapse in a structure, which may be caused due to geotechnical reasons. Several case studies (Cassidy et al 2008, Ken Ho et al 2009, Svinkin 2013, Ramesh et al 2016, which have been taken up earlier for such forensic investigation in various aspects and reason of failure cases and its remedial measures which have been found very effective with regards to economy and legalistic scrutiny also fall in same purview. In majority of case studies, it has been reported that the standard procedures which are adopted in routine testing, design and analysis are not adequate rather the test parameters, design parameters and basis of analysis will have to be in similar condition encountered at site. The scope for forensic investigation covers the following: (i) To investigate the initial reasons behind failure and establish an initial theory of failure, (ii) collection of the evidences in support of theory adopted for failure, (iii) selection of suitable testing methods and techniques to prove the evidence collection in support of failure scientifically, and (iv) To reach out at the conclusion of final reason of failure and derive the basic cause of failure based on the analysis of evidence.

General procedures of forensic engineering investigation

Normally, investigations are carried out into four stages, i.e., the early stage, evidence collection stage, analysis and confirmation of failure assumption (hypothesis) and conclusion stage.

Early stage of investigation:

The investigation process maybe started based on assumed initial failure theory or hypothesis. After establishing the initial failure hypothesis, investigation approach to collect evidences and confirmation of failure hypothesis must be planned. The testing techniques and associated equipment useful in evidence collection are identified during this stage.

Evidence collection stage:

Reaching the failure site as soon as possible after the failure happened to avoid any disturbance to the evidence. Early start of site investigation is very useful and necessary in investigation approach which comprises of visual inspection, eyewitness interviews and sample collection. By visual inspection, investigators can observe the failure scene and wreckage and take its photographs which may provide the main evidence of failure. By eyewitness interviews- eyewitness often provide the valuable evidence and feedback to investigators which are helpful in deciding the actual modes and sequence of failure. Collecting the samples is an important step in the evidence collection stage for analysis.

Analysis and confirmation of failure hypothesis

There are three approaches of analysis and confirmation of failure hypothesis by carrying out testing methods, analytical methods and expert's interviews.

i) The testing methods consist of field testing and laboratory testing. Field testing involves a series of non-destructive testing and destructive testing carried out at site to check the actual behavior of the structure. Laboratory testing involves some specific tests that are normally destructive tests to check specific properties of certain components of structure.
ii) Analytical or numerical methods comprises of design check and computational analysis. Design check includes the review of relevant documents related to the failure. Computational analysis is an approach by using computer engineering software to compute and analyze the case study.
iii) A supplementary approach to analyze the failure hypothesis is by means of expert's interviews. Normally an expert's opinion can be very valuable to the investigators to understand the cause of the failure.

Conclusion stage

Last stage is the conclusion stage when all the analysis work has been done and failure hypothesis is confirmed.

Following Fig. 1 depicts the systemic approach for the forensic investigation which is followed in the present case study, i.e., failure analysis of Hume pipe culvert head wall.

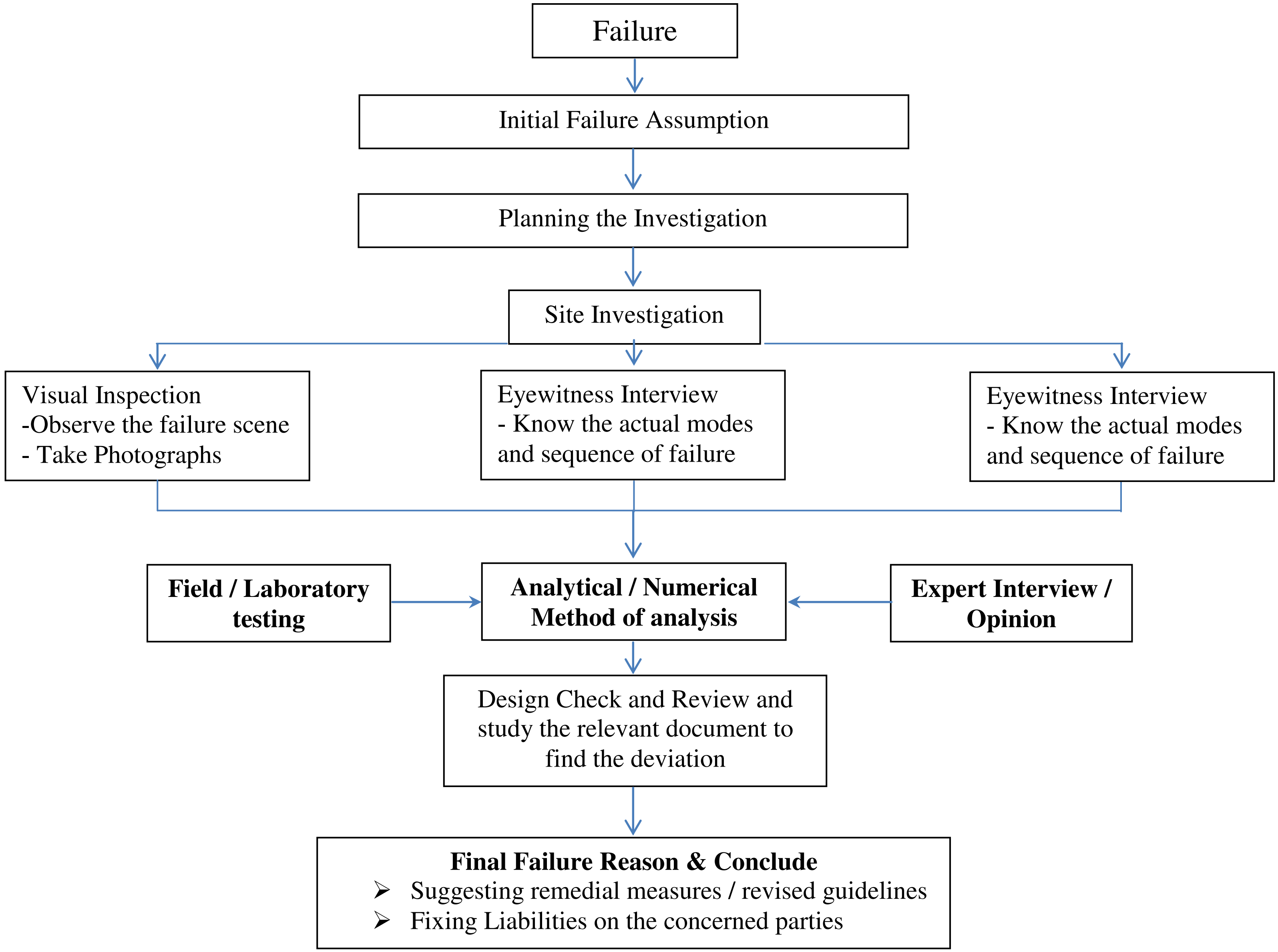

Figure 1 Investigation methodology and Flow chart for Forensic Investigation

Problem statement

1200 mm diameter Hume pipe culvert was proposed on a bypass as a part work of "Four Laning & strengthening of one of the national highways (NH)". Main function of provision of hume pipe culvert is for cross drainage of accumulated water from one side (U/S) to another side (D/S). Headwall is a part of HPC, generally, constructed to confine the road laterally at two ends of culvert and also serve as a retaining wall as protection against the scouring or undermining of fill or a flow diverting device. As per information and records, the construction of these culvert started in the month of June 2016 and was completed by the mid of July 2016. Soon after the construction, cracks were visible in the month of August 2016 during inspection. Similar observations were made at several other locations and severity of these cracks was on increase and with time, gradually, the crack was mostly 5mm to 10mm wide within a span of one month (Fig 2). This cause a serious concern to the concerned parties involved.

Figure 2 Crack development in the head wall of a typical Hume pipe culvert

Fig 3 shows typical geometrical details of Hume pipe culvert.

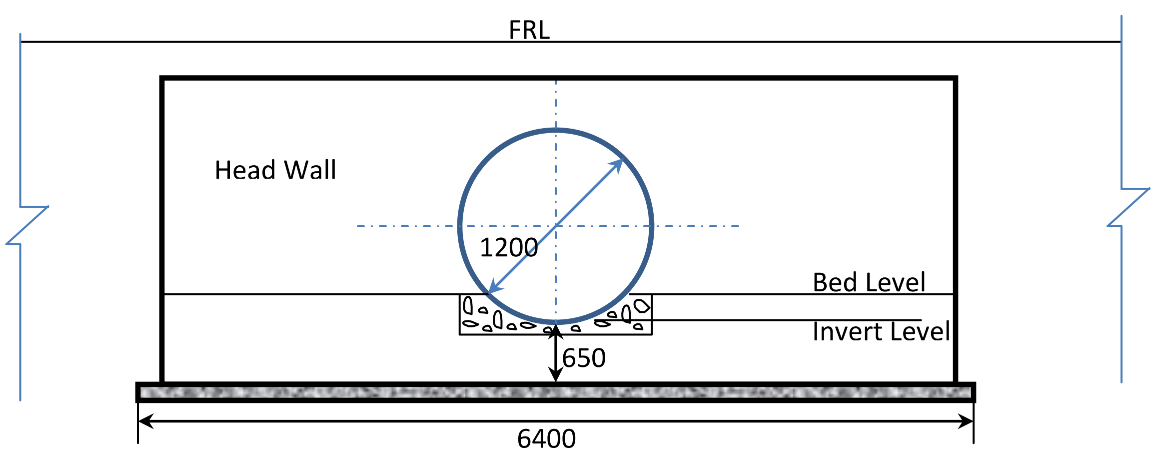

Figure 3 Typical Geometrical details of Hume pipe

Construction procedure for Head wall

Construction of HPC follows the sequence of activities like preparation of bed of foundation soil, such as, leveling and compaction of bed. Compactions are done either with roller or manual. After bed compaction, the foundation concrete (PCC, M-10 grade) of nearly 100mm are placed to support the Hume pipe. Hume Pipes are laid and jointed with each other so that there is no leakage take place (Fig 4). After laying and jointing the pipes, headwalls are constructed on both ends of culvert, serving as a retaining wall as protection against the scouring or undermining of fill or a flow diverting device

Figure 4(a) Laying of Hume pipe culvert

Figure 4(b) casting of raft for head wall

Figure 4(c) casting of raft for Hume pipe culvert

Figure 4(d) Casting of head wall

Normally, it is very rare to show sign of failure on headwall of culvert constructed with concrete or masonry at so early stage. Once cracks are visible at very early stage because of various reasons, the development of crack at a particular position of structure like headwall creates a reason for forensic investigation.

Field Observations and Testing

Settlement of both the head wall and pipe culvert was monitored during and after construction and it was observed that significant amount of settlement was noticed within a month of casting of head wall .It was also noted that there was intermittent rain soon after construction (within 15 days) of culvert and the foundation soil was submerged under water as it can be seen in Fig 2. As per drawing, the top R.L. of Head wall should be kept at 209.370 m (when head wall was casted). Following RLs at different locations of head wall were recorded (Fig 5a) and same has been reported in the following Table 1.

Fig 5(a) Measurement of settlement of head wall and comparison with RLs

Fig 5 (b) collection of soil samples for laboratory testing

Fig 5(c) In situ density measurement using sand replacement method

Fig 5 (d) Investigation for construction deficiency

Table 1 Observation on RLs (meter) of Head wall

Side	Towards Hisar	Center	Towards Sirsa	Average
LHS	209.337	209.272	209.314	209.307
RHS	209.178	209.095	209.148	209.140

It can be noted that RHS of head wall settles more than the LHS of headwall but the settlement is more or less uniform. On the LHS, the amount of differential settlement is 0.065 m and 0.042m on both side of the culvert. Similarly, on the RHS, the amount of differential settlement is 0.083 m and 0.053m on both side of the culvert. This must have caused stress concentration at the location in head wall where cracks are observed. Total amount of settlement from the original RL (209.37 m) of the head wall can be estimated as 0.063 m, i.e., 63 mm (LHS) and 0.230 m, i.e., 230 mm on the RHS.

Failure hypothesis

Based on expert opinion and review of documents, following possibilities of failure were further investigated:

- Swelling and shrinkage characteristics of soil
- Excessive settlement due to improper compaction of foundation bed
- Lateral earth pressure due to filling of material inside
- Possibilities of any construction or design deficiencies

Swelling and shrinkage characteristic

Soil samples were collected from the both side of Hume pipe culvert below head wall (Fig 5b) and its properties like grain size analysis, Atterberg's limit and free swell Index and compaction characteristics have been checked in site laboratory. Following Table 2 summarizes relevant geotechnical properties of the soil sample collected from the site:

Table 2 Geotechnical properties of soil samples collected

Geotechnical Properties	Location – A (LHS)	Location – B (RHS)
% Gravel	10.0	11.5
% Sand	22.5	22.7
% Silt & Clay	77.4	76.1
Liquid Limit	24.8	21.9
Free Swell Index	18.2	19.8
OMC	11.3%	11.3%
MDD	1.88 gm/cc	1.87 gm/cc

Field Density

Field density test by sand replacement test (IS: 2720-Part (XXVIII) was conducted at site near to foundation of headwall by investigating team. Following Table 3 summarizes the results of the analysis of the field density test.

Table 3 results of the field density test and RC values

	Location	Trial - 1	Trial - 2	Trial - 3
Bulk Density	A (LHS) B (RHS)	1.98 1.727	1.95 -	1.97 1.731
In situ moisture	A (LHS) B	9.39 8.88	8.89 -	8.80 9.31
Relative Compaction	A (RHS) B (LHS)	96.5% 91.8%	95.12% -	96.2% 92.1%

It can be noted that the soil was very well compacted on the LHS of the culvert and the RC value achieved was more than 95%. This is the reason LHS of the culvert was not much settled. On the other hand, soil on the RHS of the culvert was poorly compacted and RC value was only 92%. This must have caused excessive settlement of the head wall.

Discussion on field observations and results

- The assumption that foundation of head wall was resting on black cotton soil and because of swelling and shrinkage cracks were developed has not been found correct as fee swell index (FSI) of soil was less than 50. FSI of soil sample of both end of H.P.C. head wall was found around 18% & 19% and liquid limit was also less than specified for unsuitable soil. Hence, soil properly tested & observed does not support the assumption and the soil although had blackish appearance does not possess the swelling and shrinkage properties.

- The assumption of lateral movement of the wall was also not been supported by field observations as there was no lateral displacement noticed in head wall. Also, the space between headwall was not filled and the road way was filled on later stage of road construction after the cracks appeared.

- The hypothesis of improper compaction was also checked and it was found that the RC value achieved in the field was approximately 92%, which was much less than the specified value of 95%. Hence, there was improper compaction at the site. After the construction of head wall, soil settled to due huge pressure of head wall. The amount of settlement can be estimated form the simple calculation as shown below:

  $\Delta H = \Delta e/(1+e_o) \times H_o$

  Δe = change in void ratio = $(e_i - e_f)$

  e_i = initial void ratio and e_f = final void ratio

  Dry unit weight of the in situ soil after compaction = 1.88 × 0.92 = 1.72 gm/cc
  Assuming Gs = 2.65, the initial void ratio is estimated as, 0.54

  Assuming that the soil gets further compacted due to load of head wall and it achieves the maximum dry density, final void ratio is estimated as, 0.41
  Hence, $\Delta e = 0.13$
  The base width of the head wall = 1.25 m. Assuming zone of influence as 2B, the amount of settlement can be estimated as
  $\Delta H = 0.13 \times 1.25 \times 2 / (1+0.54) = 0.211$, i.e., 211 mm

  It can be noted that the total amount of settlement observed on the RHS of the culvert, 230 mm, is very much close to the calculated value of settlement, 211 mm.]

- By eye witness interview, it has been brought to notice that there was no proper compaction below foundation of headwall and the construction of head wall was done in a hasty manner. There was no enough time gap between casting of leveling course (P.C.C.-M15) and raft of headwall. It was also noticed (Fig 5d) that P.C.C. below Hume pipe connecting to raft of head wall was also not laid with proper compaction.

Numerical analysis

Commercially available Finite element tool PLAXIS 2D was used to perform the numerical analysis of the problem. 15-node triangular elements can be used for generating finite element mesh. Soil behavior was modeled as to follow the Mohr-Coulomb failure criterion. Tunnel element was used to the Hume pipe. Concrete Head wall was considered as elastic material with properties of M15 grade. The input properties used for the numerical analysis are summarized in Table 4.

Table 4 Input properties for the numerical analysis

Properties	**values**
Material behavior of foundation soil	Mohr-Coulomb
Elastic modulus of soil	5 MPa
Poison's ratio	0.40
Cohesion	0.1 kPa
Friction angle	28°
EA (plate element for tunnel)	32.25×10^5 kN/m
EI (plate element for tunnel)	60.47×10^2 kN-m^2/m
E (M15 Grade concrete)	$5700 \sqrt{\square_{ck}}$ (MPa)
Poison's ratio	0.15

Fig 6 shows the step followed in the numerical analysis of the Hume pipe culvert. From results of the analysis, it can be noted that both compressive and tensile stresses are developed in the head wall. Blue shade shows tensile stresses developed and red shades indicates development of compressive stresses in the Head wall. It can be noted that the tensile stresses developed in the head wall is at the location of the crown of Hume pipe where the crack was developed. As we know that concrete cannot take tension, development of tensile stress (53 kN/m^2) has caused severe cracks in the head wall. Based on the study, provision of reinforcement can be suggested at the location of tensile stresses development in the head wall.

Conclusion

The most credible hypothesis regarding this case study i.e. failure of the head wall was found that crack development in headwall has occurred because of lack of proper compaction of soil below foundation of culverts and no time gap between the casting of headwall and its foundation. The preparation of bed foundation was not carefully done and even intermittent rain has made the soil mass saturated which has caused the primary consolidation in 61 days. This has reflected in the form of cracks in headwall.

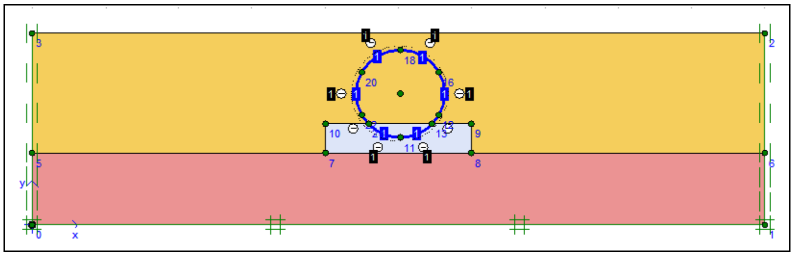

Figure 6(a) Finite Element model for the numerical analysis of Head Wall

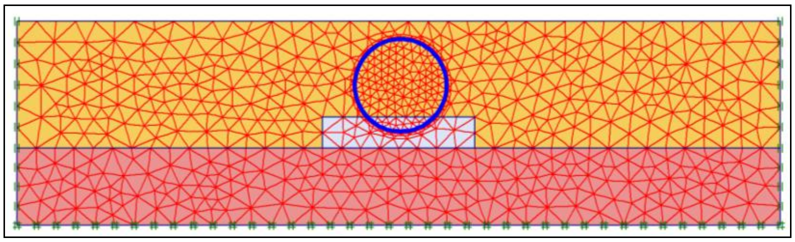

Figure 6(b) 15 Node triangular element for the discretization of model

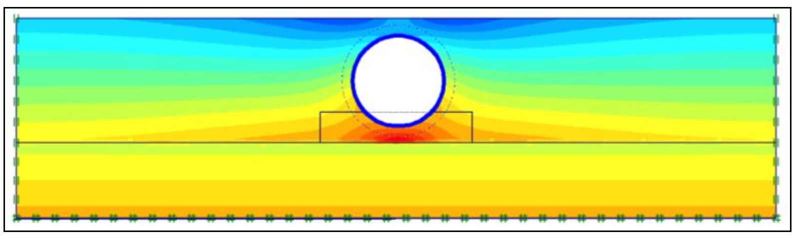

Figure 6 (c) Stress concentration in Head Wall(blue shade for tensile stresses)

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