

Structural Evaluation and Root Cause Analysis of Vehicular Box Culvert (VBC) Defects in Section 6A of ECRL Project

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Abstract

This research investigates concrete defects in Vehicular Box Culverts (VBCs) within Section 6A of the East Coast Rail Link (ECRL) project. A significant defect was identified at Culvert 192 (CH384+580), where cracks were found in the top slab and wing wall. The study aims to comprehensively analyze the types and causes of concrete defects in the VBCs within work zone 2 of Section 6A. The methodology involved detailed site visits and inspections of 21 VBCs, documenting defects such as shrinkage cracks, water seepage, and discoloration. The quantitative analysis, presented through bar and pie charts, revealed discoloration as the most frequent defect, with medium severity levels being the most common. Contributing factors to these defects include poor soil compaction, inadequate waterproofing, and substandard construction practices. An AutoCAD 3D model was employed to illustrate loading conditions and their impact on VBC settlement, emphasizing the effects of vehicular loads and soil pressure. The findings indicate that most defects are manageable through standard maintenance, although some structural issues, such as settlement cracks, present significant risks. This research highlights the need for improved construction practices and maintenance strategies to enhance the durability and integrity of VBCs in large-scale infrastructure projects like the ECRL.

1. Introduction

Vehicular Box Culverts (VBCs) are essential in railway projects, contributing significantly to the efficiency, safety, and longevity of the infrastructure by enabling the passage of vehicles, including trains, over roads, water bodies, or other obstructions [17]. In the ECRL project, VBCs facilitate safe crossings for the public, villagers, and farmers, ensuring uninterrupted traffic flow over and under rail tracks. However, these structures can experience settlement and concrete defects due to factors related to design, construction, and environmental conditions. Settlement often results from inadequate foundation support, improper compaction of surrounding soil, or changes in underlying soil conditions [18].

Timely identification of these defects is crucial to maintaining the project's timeline and ensuring the long-term functionality and structural integrity of the railway infrastructure. During a site visit to Work Zone 2 of the Section 6A ECRL project, a notable concrete defect was identified at Culvert 192, located at CH384+580. The defect

manifests as cracks in the top slab and wing wall area, highlighting structural vulnerabilities within the VBCs. These issues, including cracks, scaling, and other forms of deterioration, raise concerns about the long-term performance and integrity of the VBCs in this zone. Untreated defects pose risks to structural integrity and carry potential financial implications, emphasizing the economic impact of unresolved infrastructure issues. Understanding the root causes of these defects is paramount, as they compromise the structural robustness and overall functionality and safety of the infrastructure. By examining and understanding these causes, the research provides essential insights for targeted remediation strategies. Addressing these challenges holds broader implications for project timelines, safety, and cost-effectiveness. Mitigating defects can minimize construction delays, enhance safety measures, and reduce the risk of accidents or failures. Effective remediation strategies based on this research can lead to cost savings by optimizing resource allocation and minimizing future repairs or maintenance.

This research has two main objectives: first, to analyze the defects present in VBCs within Work Zone 2 of Section 6A in the ECRL project; and second, to investigate the contributing factors associated with these observed defects. The study focuses specifically on the concrete defects and settlement behavior of VBCs within the defined boundaries of Work Zone 2, spanning from CH364+514 to CH401+579. It will involve analyzing concrete defects through several site visits and conducting a thorough examination of the root causes by reviewing past articles, technical specifications, method statements, and on-site observations. The research aims to identify the most common types of defects, the severity levels, the locations or components most affected, and the contributing factors for each type of defect.

The structural design of Vehicular Box Culverts (VBCs) incorporates several essential components that ensure their integrity and functionality as shown in Fig. 1. These include the top slab, which distributes loads from vehicles and traffic, the side walls providing vertical boundaries and structural support, the bottom slab acting as a sturdy foundation, and wing walls extending from the side walls to guide water or traffic flow and offer additional support [6]. Transition slabs in some designs facilitate smooth transitions and enhance stability. In the ECRL Section 6 project, the construction of VBCs involves meticulous procedures and materials such as ready-mix concrete, steel reinforcement bars, polyethylene foam board, rubber water stops, and waterproof materials, as outlined in the Method Statement of Section 6 ECRL Construction of Cast In-Situ Culvert revision 04. The process includes setting out activities, excavation, foundation preparation, waterproofing, formwork installation, concreting, and curing, followed by the application of a waterproof layer to ensure durability. Technical specifications cover aspects like waterproofing, concrete workability and compressive strength, steel reinforcement, and earthwork, with stringent quality control measures such as mill certificates and laboratory testing to ensure compliance with standards.

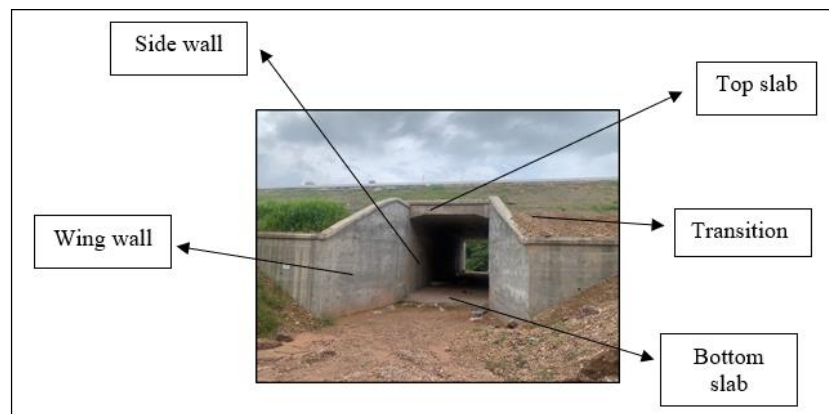


Fig. 1 Components of VBC

Relevant research on "Settlement Analysis of Pipe Culvert Situated in Soft Clay Treated with Prefabricated Vertical Drains" addresses challenges of soft soils, known for low shear strength and high compressibility, in geotechnical engineering. Historically, such soils were avoided to mitigate settlement issues, but rising construction demands necessitate their use, prompting soil improvement techniques like preloading with wick drains to enhance bearing capacity and minimize settlements [14]. The study evaluates the effectiveness of prefabricated vertical drains in accelerating consolidation and reducing settlements through finite element-based numerical modeling and field monitoring. Results show that consolidation duration, wick drains, and granular fill thickness influence settlement performance, with numerical analysis closely matching field data initially but showing minor discrepancies later as illustrated in Fig. 2. The study highlights the importance of empirical data for accurate engineering decisions and demonstrates that wick drains significantly reduce settlements by

accelerating pore water dissipation and soil compression. Closer wick drain spacing facilitates faster consolidation rates, underscoring the effectiveness of this soil improvement technique [14].

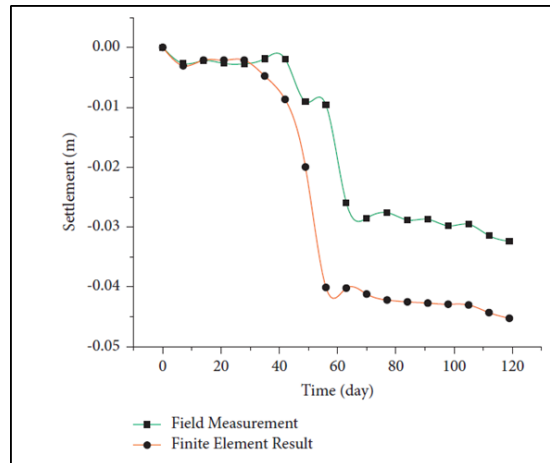


Fig. 2 Comparison of site monitoring settlement data with finite element result [14].

2. Methodology

The methodology section outlines the systematic approach employed in this research to analyze and address the defects in Vehicular Box Culverts (VBCs) within Work Zone 2 of Section 6A in the ECRL project. Through site visits and detailed inspections, various concrete defects will be documented and categorized. Additionally, a review of technical specifications, method statements, and past research will provide context and support for the findings.

2.1 Quantitative Research with Site Visit

The on-site investigation involved a meticulous site visit to Work Zone 2 of Section 6A in the ECRL project, focusing on the analysis of defects in VBCs. This comprehensive approach aimed to visually identify and document any observable issues affecting the structural integrity of the VBCs. During the site visit as shown in Fig. 3, detailed records were made, capturing photographs of defects and their locations. A systematic checklist was employed to ensure consistency in identifying various types of defects, including cracks, spalling, and other structural deteriorations. The on-site inspections served as a crucial aspect of the research, providing firsthand data on the condition of VBCs within the specified work zone. This method facilitates a thorough understanding of the physical aspects of defects, complementing the insights gathered from the concurrent online survey. In this research, there are 21 VBCs have been selected which located ranging from CH367+012 until CH400+250 as samples. Parameter used for type of defect is for concrete only and the severity level applied to study how severe defects on VBCs in work zone 2 of section 6A ECRL project is divided into four levels which are very slight, minor, medium and major. Very slight means that absence of defects or defects with no expression, minor means that defects prejudicial to aesthetics, medium means that defects prejudicial to use or comfort and severe means that defects that endanger health or safety. Quantitative research methodology is a systematic approach employed to investigate phenomena across various domains by collecting, analyzing, and interpreting numerical data. At its core, this methodology relies on well-defined hypotheses or research questions that guide the inquiry process. Researchers gather quantitative data through on-site observation to ensure the data's reliability and consistency through standardized measurement tools and techniques. Once collected, statistical analysis techniques are applied to uncover patterns, relationships, and trends within the data. Interpretation of the statistical findings allows researchers to draw conclusions and assess their significance in relation to the research objectives. Ultimately, the results are presented using visual aids and clear reporting to communicate the findings effectively and contribute to empirical knowledge in various fields. Software used to produce the bar chart and pie chart for data analysis purpose in this research is Microsoft Excel.



Fig. 3 Picture taken during site visit

2.2 AutoCAD 3D Drawing

AutoCAD 3D drawing was utilized to model the VBC located at CH377+430 as illustrated in Fig. 4. The dimensions for the VBC were carefully taken from this specific example to create an accurate representation of the structure. This 3D model serves as a vital tool for visualizing and analyzing the different types of loading applied to the VBC, which are key factors contributing to its settlement. The AutoCAD 3D drawing illustrates the geometric details of the VBC, including its length, width, height, and wall thickness. By applying various load simulations such as vehicular load, soil pressure, and environmental loads, the model helps in understanding how these forces affect the structural integrity of the VBC. The detailed visualization allows for a comprehensive analysis of stress distribution and potential weak points within the structure. Using this model, it was possible to demonstrate that the combination of these loads can lead to settlement issues. For instance, the repeated application of vehicular loads can cause compaction of the underlying soil, leading to settlement cracks. Similarly, the weight of the soil and water pressure around the VBC can cause additional stress, contributing to the formation of settlement gaps and other defects. By incorporating the AutoCAD 3D drawing into the study, we can better illustrate the real-world impacts of various loads on the VBC at CH377+430, thereby providing a clearer understanding of the factors leading to settlement.

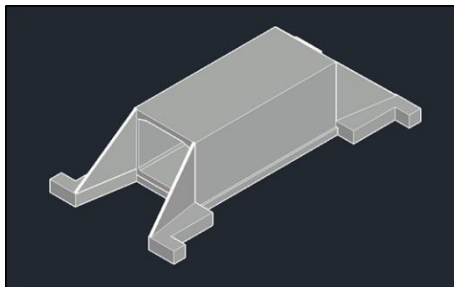


Fig. 4 3D drawing of VBC CH377+430 by using AutoCAD

3. Results and Discussion

The results and discussion section present the findings from the comprehensive analysis of defects in Vehicular Box Culverts (VBCs) within Work Zone 2 of Section 6A in the ECRL project. This section details the types and frequencies of defects observed, the severity levels, and their specific locations within the culvert structures. Additionally, it examines the contributing factors identified through site inspections, laboratory tests, and reviews of technical documentation.

3.1 Frequency for Each Type of Defects

Fig. 5 shows the bar chart that illustrates the frequency of various types of concrete defects observed in VBC within work zone 2 of section 6A of the ECRL project. The x-axis represents different types of concrete defects, while the y-axis shows the frequency of these defects, measured in numbers (Nos). From the bar chart, several key observations can be made. The most frequently observed defect is discoloration, with a count of six instances. The category of "no concrete defect observed" is the second most common, with a frequency of five. Shrinkage cracks

were noted four times, while both tie rod holes and water seepage were recorded three times each. Settlement cracks occurred twice, and scaling, delamination, blistering, pop out, and settlement gaps were each observed once. These observations highlight the variety of defects that can occur in concrete structures, even within a single project section. The trends observed in the bar chart suggest that certain defects, such as discoloration, are more prevalent in the VBCs of section 6A. This could be due to several factors, including the use of calcium chloride as an admixture, intended to accelerate the setting time of concrete, often leads to uneven color distribution according to article from Portland Cement Association (2001).

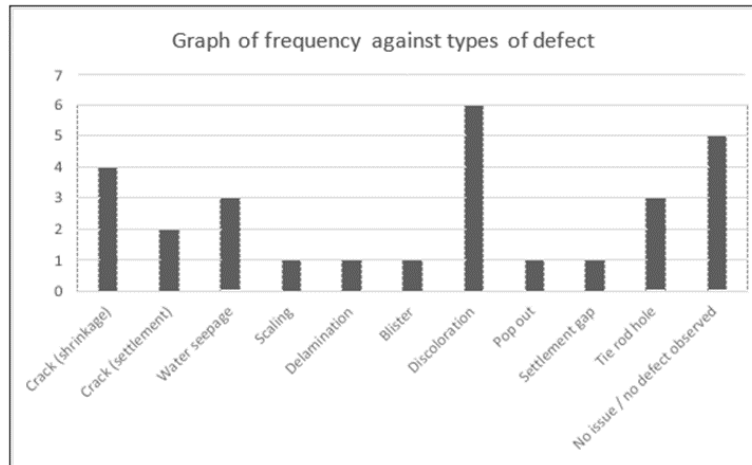


Fig. 5 Bar chart of frequency against types of defect

In the context of the ECRL project, varying amounts of calcium chloride across different batches of concrete might have caused significant discoloration issues, particularly if the admixtures were not properly mixed. Additionally, variations in the alkali content of the cement used can react with other components in the concrete mix, leading to surface discoloration. High alkali content, common in large-scale projects where materials are sourced from different suppliers, could contribute to this defect. Proper curing practices are essential to maintain uniform moisture levels in concrete, yet inadequate or inappropriate curing methods, such as insufficient water curing or premature drying, can lead to surface discoloration. Furthermore, the presence of a wet substrate or base on which the concrete is poured can lead to uneven moisture distribution, impacting the hydration process of the concrete at different rates across the surface. This issue is particularly relevant in large-scale projects like the ECRL, where site conditions can vary significantly. Inconsistent water-cement ratios during mixing or at different stages of the pour also contribute to color variations. This inconsistency can be exacerbated by the sheer scale of the project, where multiple teams and equipment are involved in concrete mixing. On the other hand, more serious structural defects like settlement cracks and delamination are less frequent but still present and significant.

3.2 Percentages of Severity Level

The percentages of severity level are illustrated into pie chart as shown in Fig. 6. The categories shown in the pie chart are the severity levels which are very slight, minor, medium, and severe. The units of measurement are percentages based on the frequency of each severity level occurrence. The pie chart reveals several key insights into the severity levels of the observed defects. The severity level with the highest percentage is medium, accounting for 35.71% of the defects. This is followed by minor severity at 32.14%, very slight at 17.86%, and severe at 14.29%. These observations indicate that the majority of defects fall within the medium and minor severity levels, with severe defects being the least common. The proportions observed in the pie chart likely exist because each VBC exhibits different types and extents of defects, leading to varying severity levels. Medium and minor severity levels are more common, whereas severe defects, although present, are less frequent. The majority of the defects in the VBCs of work zone 2 of section 6A of the ECRL project fall within the medium severity level, which accounts for 35.71% of the observed defects. Several factors contribute to this predominance.

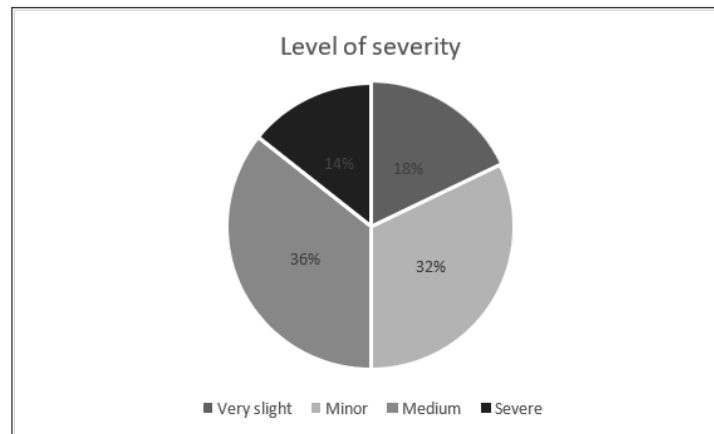


Fig. 6 Pie chart of severity level

Firstly, medium severity defects such as shrinkage cracks, water seepage, and tie rod holes are relatively common in concrete structures due to typical construction processes and environmental conditions. Shrinkage cracks, for instance, occur as concrete dries and hardens, a natural phenomenon influenced by the total water content and environmental conditions like temperature and humidity. Similarly, water seepage can result from poor waterproofing practices or wear and tear over time, leading to water penetrating through small cracks or gaps. Tie rod holes are another frequent issue, as they result from the removal of formwork rods, leaving holes that can develop into defects if not properly filled and maintained. These types of defects, while impactful, do not critically compromise the structural integrity of the VBCs, categorizing them as medium severity. They are more serious than minor defects, which are typically aesthetic, but they do not pose immediate health or safety risks like severe defects. The prevalence of medium severity defects suggests that while there are notable issues, they are primarily manageable through standard maintenance and repair practices. This implies that the construction quality is generally acceptable, but there are areas needing improvement to prevent these medium-level issues from escalating. Understanding which severity levels are most and least frequent helps in assessing the overall condition of the VBCs in work zone 2 of section 6A of the ECRL project. The predominance of medium and minor severity defects suggests that while there are issues to address, the majority are not critically severe. This can guide maintenance and repair efforts, prioritizing areas that require more immediate attention due to severe defects.

3.3 Percentages of VBC Components That Experienced Defects

Fig. 7 shows the percentages for location of defects, separated into three locations or components of VBC which are wing wall, top slab and wall. The units of measurement are percentages based on the frequency of defects occurring in each location. The pie chart reveals several key insights into the locations of the observed defects. The component with the highest percentage of defects is the wing wall, accounting for 55.17% of the total observed defects. This is followed by the top slab with 27.59%, and the wall with 17.24%. These observations indicate that defects are more commonly found in the wing wall compared to the top slab and wall. The proportions observed in the pie chart likely exist due to the specific structural and environmental conditions each component is exposed to. The wing wall, having the highest percentage of defects, might be more prone to issues due to several key factors. Firstly, the wing wall is more exposed to environmental conditions compared to the top slab and wall. Being positioned externally, the wing wall faces direct exposure to weather elements such as rain, wind, and temperature fluctuations. This constant exposure can lead to increased wear and tear, making the wing wall more susceptible to defects like discoloration, scaling, and cracking due to thermal expansion and contraction. Additionally, the design of the wing wall structure for the VBCs in the ECRL project does not incorporate reinforcement bars. The absence of reinforcement can reduce the structural resilience of the wing wall, making it more prone to cracking and other forms of damage under load-bearing conditions. Reinforcement bars are crucial for distributing stress and enhancing the tensile strength of concrete, and their absence can lead to a higher incidence of defects. Moreover, the wing wall often bears significant load-bearing responsibilities, supporting not only the weight of the soil and infrastructure above but also any lateral forces exerted by the surrounding environment [18]. This additional stress can exacerbate defects, particularly in the absence of reinforcement.

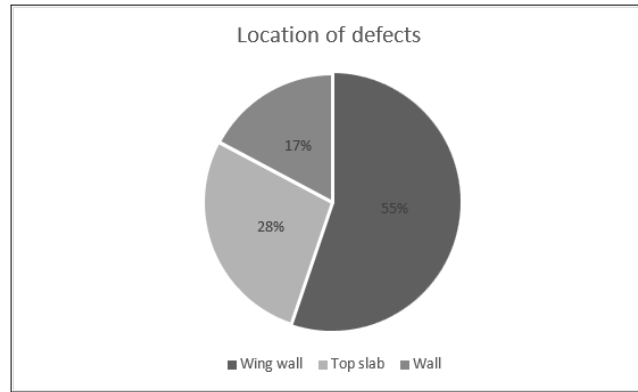


Fig. 7 Pie chart of defects location

There are 10 different types of defect and each of the defect has their factors that may contribute to the defects to occur. Analyzing the causes of defects observed in the VBC within work zone 2 of section 6A of the ECRL project provides valuable insights into potential improvements in construction practices and maintenance. Various defects have been detected, each with specific causes derived from theoretical knowledge and readings from different sources. According to an article from Portland Cement Association (2001), shrinkage cracks were observed in VBC A, B, K, and M, and are attributed to two main factors, drying shrinkage and plastic shrinkage. Drying shrinkage occurs due to the total water content in the concrete, where higher water content leads to increased shrinkage as the water evaporates. Plastic shrinkage cracks, on the other hand, occur before final finishing under conditions of high wind, low humidity, and high temperature, causing the surface moisture to evaporate faster than it can be replaced, resulting in surface shrinkage greater than that of the interior concrete. Settlement cracks were noted in VBC D and F, caused by the settlement of the formation under the VBC. This type of settlement is due to poor soil compaction and the geotechnical properties of the soil, which result in soil settling over time and causing cracks in the VBC structures [3]. Water seepage defects were found in VBC A, C, and M, and are linked to poor installation practices, inadequate waterproofing, and natural wear and tear. Poor installation can lead to gaps or cracks that allow water to seep through, compromising the integrity of the concrete slabs [7]. Scaling, detected in VBC B, occurs due to the physical action of hydraulic pressure from water freezing within the concrete, leading to the general loss of surface mortar. This is typically seen in areas exposed to freezing and thawing cycles, where the aggregate becomes exposed and stands out from the concrete [20]. Delamination, observed in VBC F, results from bleed water and air being trapped below a prematurely closed mortar surface, usually caused by finishing the surface before all the bleed water has escaped [10]. Blistering, found in VBC H, is caused by an excess amount of entrapped air within the concrete, resulting from insufficient or excessive vibration during compaction. In this case, inadequate vibration failed to release the air, or over-vibration left the surface with excessive fines, leading to blister formation according to an article from Portland Cement Association (2001). Discoloration, noted in VBC H, J, L, P, R, and S, can be caused by several factors including calcium chloride admixtures, cement alkalis, hard-troweled surfaces, inappropriate curing, a wet substrate, variations in the water-cement ratio at the surface, and changes in the concrete mix [11]. Pop outs in VBC K are caused by porous aggregate absorbing moisture or freezing under moist conditions, leading to swelling and internal pressure that ruptures the concrete surface. Tie rod holes, observed in VBC C, I, and K, are left when tie rods are removed after concrete curing. These holes are typically patched, but ground movement and freeze/thaw cycles can cause the patching to break down over time, leading to visible defects. Identifying specific causes for each type of defect enables targeted interventions to prevent recurrence. By addressing these causes, project engineers and contractors can enhance the durability and quality of VBC structures, ensuring longer-lasting infrastructure and reducing maintenance costs over time. This analysis underscores the importance of continuous monitoring and quality control throughout the construction process to identify and rectify potential issues before they manifest as defects.

Settlement gaps, found in VBC G, occur due to the settlement of the formation under the VBC, similar to settlement cracks, caused by poor compaction and the soil's geotechnical properties, resulting in shifts in VBC components and creating gaps between them. The settlement of the VBC in work zone 2 of section 6A of the ECRL project can be attributed to various types of loading applied to the structure, including dead load, live load, soil pressure on the side walls, surcharge due to live load, and uniform lateral load on the side walls as shown in Fig. 8. The dead load consists of the self-weight of the VBC structure, including the embankment and deck slab, exerting continuous pressure on the foundation. This can lead to gradual settlement over time, especially if the underlying soil is inadequately compacted or has poor load-bearing capacity. The weight of the embankment, deck slab, and track load are considered as uniformly distributed loads on the top slab, with the uniform soil reaction on the

bottom slab further adding to this load. Inadequate support or variations in soil reaction can cause uneven settlement [18].

Live load, as calculated according to IRC 21-2000, considers the contact area of vehicle wheels or tracks and their dispersion along the traffic direction. If load dispersion overlaps due to miscalculations, it can cause concentrated loads, leading to localized settlement if the soil cannot uniformly support these pressures. The self-weight of the side walls acts as a concentrated load, producing a uniform soil reaction on the bottom slab. Variations in soil properties or poor compaction beneath the side walls can lead to differential pressure distribution, resulting in uneven settlement [18]. Earth pressure on the vertical side walls, calculated using Coulomb's theory, is based on the coefficient of active earth pressure, soil density, and the height of the culvert. This earth pressure can exert significant lateral forces on the side walls, and any changes in soil properties or the presence of voids or weak layers can lead to differential settlement. Uniform lateral pressure on the vertical side walls, resulting from embankment loading and live load surcharge, can also contribute to differential settlement if the pressure is not uniformly distributed or if the soil beneath lacks adequate bearing capacity [18].

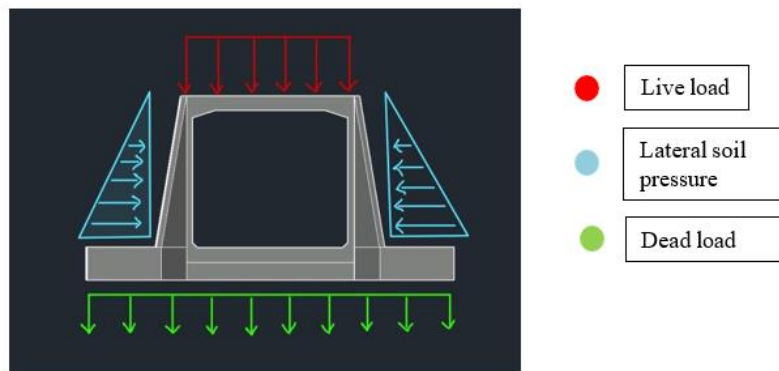


Fig. 8 Illustration of different types of loading on VBC using AutoCAD

4. Conclusion

This research has provided valuable insights into the defects and contributing factors affecting VBCs within Section 6A of the ECRL project, aligning with the objectives of identifying and analyzing these defects. We found that VBCs, critical components of railway infrastructure, are prone to various defects, including discoloration, shrinkage cracks, and settlement gaps, which can compromise their structural integrity and longevity. Discoloration was the most frequently observed defect, attributed to factors such as improper admixture usage and inadequate curing practices. Medium severity defects, like shrinkage cracks and water seepage, were prevalent due to typical construction processes and environmental conditions.

In conclusion, this research successfully achieved its objectives by analyzing and identifying the defects in VBCs within Section 6A of the ECRL project and investigating their contributing factors. It provides a comprehensive understanding of the structural challenges faced and proposes practical solutions to mitigate these issues. The findings reinforce the initial hypothesis that various construction and environmental factors significantly impact the integrity of VBCs, highlighting the need for meticulous construction and maintenance practices.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Author M.H.A.M.S., Author M.N.Y; **data collection:** Author M.H.A.M.S., Author A.A.; **analysis and interpretation of results:** Author, M.H.A.M.S.,

Author M.N.Y, Author A.A; **draft manuscript preparation** Author M.H.A.M.S., Author M.N.Y, Author A.A. All authors reviewed the results and approved the final version of the manuscript.

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