Design of GRS bridge abutment using river debris as backfill material

Stanislav Lenart*[1] *and Siva Ram* Karumanchi[1]

[1] Slovenian National Building and Civil Engineering Institute (ZAG), Dimičeva 12, SI-1000 Ljubljana, Slovenia

Abstract. The Horizon Project CIRCUIT (2024) seeks to construct a new bridge on a local road in the municipality of Črna na Koroškem, Slovenia, replacing the existing structure over a torrential creek. The project incorporates geosynthetic-reinforced soil (GRS) with cast-in-place concrete full-height rigid facing (FHR) for the bridge abutments, providing robust scour protection. In August 2023, severe flooding caused by heavy rainfall deposited large quantities of river debris—comprising silty sand and gravel—classified as non-hazardous inert waste in the area designated for the bridge construction. To enhance sustainability, this debris has been repurposed as backfill material for the new GRS bridge abutments. This paper details the material testing and design considerations for constructing the bridge abutments under these revised conditions.

1 Introduction

The growing popularity of geosynthetic-reinforced soil (GRS) bridge abutment systems [1] in civil engineering infrastructure is largely attributed to their exceptional performance and low maintenance requirements. Authors of [2] provided recommendations for GRS bridge-supporting structures regarding maximum vertical settlement of footing under 0.5% and lateral deflection to 1% of wall height, respectively, and allowable settlement of approach slope (bump) is restricted to 1/200. The flexible GRS bridge abutments with selected fill material for bridge approaches in highway applications perform well. The GRS bridge abutment systems need 'select' fill materials with lesser finer materials and high shear strength characteristics. The non-availability of these materials locally has led contractors to source them from faraway regions. As Slovenia progresses in infrastructure projects across highways, railways, slope protection, and irrigation, challenges like resource depletion from overuse of quality raw materials, rising costs, and an increased carbon footprint from transportation demand urgent attention. Addressing these challenges involves the use of locally sourced fill materials as reinforced design fills, along with modified geosynthetic composites for GRS bridge abutments, to save high-quality raw materials, encourage theoretical exploration, and embrace innovative practices. In August 2023, Slovenia faced record-breaking rainfall, resulting in devastating flooding and landslides. Over a hundred bridges and numerous supporting structures were severely damaged. [3].

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*Corresponding author: stanislav.lenart@zag.si

More than 170 major landslides occurred, and over 400 buildings were either destroyed or rendered uninhabitable. In the municipality of Črna na Koroškem, a local bridge that was entirely destroyed by the flooding, with flood-induced erosion critically weakening the soil embankment supporting the structure, as depicted in Fig. 1, was selected for reconstruction within CIRCUIT project. The Mežiška Valley flood left around 25,000 tons of sludge, primarily sand and gravel, classified as non-hazardous inert waste. This debris is now being repurposed for construction under the CIRCUIT project, a collaborative effort led by ZAG and its associated stakeholders to build new GRS bridge abutments. GRS bridge abutments consist of three primary components: the fascia, geosynthetic reinforcement, and compacted backfill material [4]. International standards, including [5-7], outline detailed procedures for designing, selecting materials, and constructing GRS bridge abutments for highway applications. These structures can be completed within weeks, regardless of weather conditions. So far, GRS abutments with full-height rigid (FHR) facings [8] have predominantly been used in Japan, while flexible facings, such as concrete modular blocks, are the preferred choice in the USA and other countries.

Fig. 1. Damaged Bridge abutment in the municipality of Črna na Koroškem, Slovenia (2023)

While FHR facings are costly to construct, flexible facings offer less resilience. As a part of the CIRCUIT project for constructing the damaged bridge, the innovative solution of integrated GRS bridge abutments involves semi-FHR facings reinforced with geosynthetic anchors within the GRS structure. Semi-FHR facings combine local stiffness adaptability with cost efficiency, balancing reduced construction costs and enhanced structural resilience. These facings lower construction costs significantly while maintaining the ability to resist horizontal loads and optimize vertical load distribution. By adopting this innovative construction method, erosion at the abutment foundations will be significantly reduced, eliminating the need for traditional anti-erosion techniques like stone protection. The use of river debris as backfill material exemplifies circular economy principles and fosters sustainability in construction. Further, it reduces dependence on imported fill, lowers transportation costs and carbon emissions, and decreases the overall environmental impact [9]. It has been established through the research [1] that GRS systems can function efficiently with marginal or non-select fill materials, provided that suitable design and testing methodologies are applied. This paper details the material characterization, design considerations, and experimental procedures for constructing GRS bridge abutments using river debris. The study includes material characterization of river debris through conventional sieve analysis, modified proctor tests, and drained triaxial tests to evaluate the mechanical properties of the debris. The findings demonstrate the feasibility of using river debris as a sustainable alternative to conventional backfill materials.

2 Design Consideration for the Construction of FHR GRS abutments

One of the main challenges in using river debris as fill material in GRS structures is addressing its potential environmental impacts [10]. This includes assessing soil toxicity through leachate testing to identify its chemical composition and evaluating the durability of geosynthetic materials when in contact with river debris. A previous case study [11] demonstrated that, despite high alkalinity (pH 12), alternative or secondary raw materials do not affect the strength characteristics of geogrids. In addition, tensile tests conducted on 2×15 specimens of geogrid yarns with partially removed coatings revealed no significant difference in tensile strength before and after long-term exposure to the hyper-alkaline environment. The primary considerations for backfill selection in GRS structures include achieving adequate compaction, ensuring drainage, improving workability, and enhancing shear strength. Rounded flood debris aggregates can significantly influence the shear strength of the GRS composite. Empirical validation of the ultimate vertical capacity is necessary due to the unique interaction between the fill and the geosynthetics. To evaluate the innovative solutions proposed for constructing GRS bridge abutments, large-scale performance tests of the geosynthetic reinforcement and backfill material are essential [12,13]. The staged construction of GRS retaining walls (RW) with full-height rigid (FHR) facings has been a long-standing practice in Japan, unlike in other regions of the world [14]. The testing protocols (Fig.2(a)) applied in developing the innovative GRS bridge abutment solution draw from those described in Lenart et al. (2016)[15]. In this prior study, the original bridge was demolished and replaced with a new structure comprising a reinforced concrete slab and geosynthetic-reinforced soil abutments, as shown in Fig.2(b). The design process included considerations for the dead weight and traffic loads of the bridge.

Fig. 2. (a) Large-scale testing **(b)** Construction of GRS abutments adopted from Lenart et.al (2016) [15]

3 Material Characterisation

The river debris accumulated from the flooding event was sieved and sourced at a site in the municipality of Črna na Koroškem, Slovenia, near the construction site, as shown in Fig. 3(a). The gradation curve of the sourced material is illustrated in Fig.

3(b). The key parameters obtained from the gradation curve, the coefficient of uniformity (Cu), and the coefficient of curvature (Cc) were 12.3 and 1.5, respectively. The gravel fraction (2 mm to 63 mm) constituted 69.3%, while the sand fraction (0.063 mm to 2 mm) comprised 27.6%, indicating that finer particles were less than 5%. Based on these results, the river debris was classified as well-graded gravel (GW) according to the Unified Soil Classification System (USCS). Modified Proctor tests were conducted to determine the optimum moisture content and maximum dry density of the river debris, indicating an optimum moisture content of 4.9% and a maximum dry density of 2.41 g/cm^3. These values fall within acceptable limits for use in geosynthetic-reinforced soil (GRS) abutments. The geogrid used in the reinforced soil triaxial test had tensile strengths of 150 kN/m in the main direction (MD) and 25 kN/m in the cross-main direction (CMD) at 6% strain, with the MD achieving 45 kN/m at 2% strain. The mesh size in both MD and CMD was 25 mm. The flexible geogrid was composed of polyvinyl alcohol (PVA) in the MD and polypropylene (PP) in the CMD.

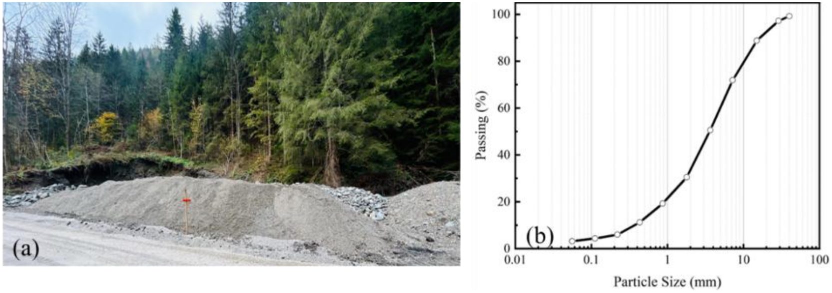

Fig. 3. (a) Sourced river debris material **(b)** Gradation curve of the river debris material

4 Large-Scale Triaxial Tests

Large-scale triaxial compression tests, conducted under drained conditions, were performed on unsaturated specimens using monotonic loading and unloading. The testing will be carried out in two stages: unreinforced river debris material was tested in the first phase, while reinforced river debris material will be tested in the second. At the Department of Geotechnics, ZAG, Slovenia, a large-scale multifunctional testing setup was developed. The apparatus, shown in Fig. 4, includes a unidirectional movable base, hydraulic vertical and horizontal actuators, load cells, and advanced data logging systems supported by a frame for applying normal and horizontal loads. It features a 100 mm base displacement capacity and a load range of 0 to 200 kN, with the added ability to perform cyclic displacement and load testing. This versatile setup allows for large-scale monotonic and cyclic triaxial tests, as well as direct shear and cyclic simple shear tests.

As shown in Fig. 5 (a-d), the large-scale triaxial test specimen is prismatic in shape, with dimensions of 400 × 400 × 700 mm. The rubber membrane serves as a protective layer and is sealed with a waterproofing silica gel. For the test with reinforced geogrid soil, the geogrids were placed at a spacing of 300mm between them (shown in Fig. 4). As illustrated in Fig. 5; the instrumentation includes three vertical displacement transducers arranged at the top to measure global strain characteristics. Local strains are measured using horizontal and vertical transducers attached to the sides of the flexible membranes, as shown in Fig. 5(f). All tests are planned as drained triaxial compression tests at fixed confining pressures of 50 kPa, representing the confinement levels at the centre of the considered GRS bridge abutment with a height of 5m. A partial vacuum was used to apply confining pressure as backpressure, with the vacuum applied at the bottom of the specimen and measured at the top. Preparing triaxial specimens with river debris material involved oven and air-drying to achieve complete dryness. Samples were compacted to 95% of the desired dry density (2.35 g/cm³) with an optimum moisture content of 6.8%, maintaining consistent falling height and compaction effort. Each 15 kg batch was mixed in a mixer before being compacted in a large triaxial mould. Scraping the compacted surface after each batch ensured effective interlocking between layers. The deformation properties were defined based on the results of the large-scale triaxial tests. Additional key parameters, such as maximum shear resistance, the initial load response, and equivalent elastic properties from small unloading and reloading cycles, will be analysed to assess their impact on the behavior of the composite material in constructing bridge abutments.

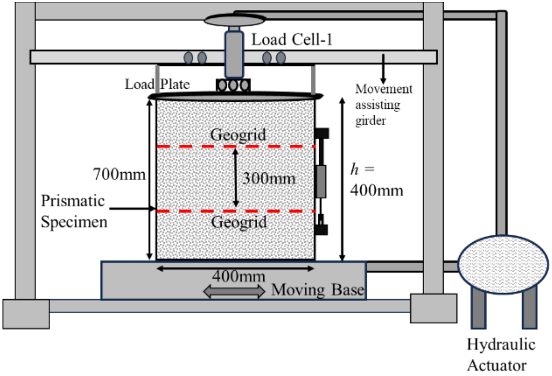

Fig. 4. Schematic Illustration of Multifunctional large-scale Triaxial Test Setup

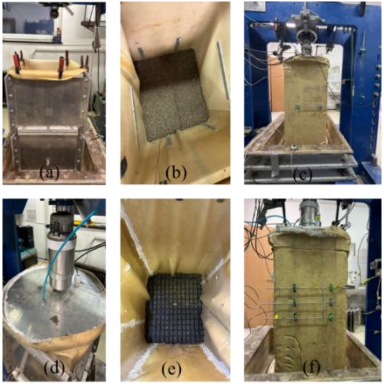

Fig. 5. Triaxial Specimen Preparation and Instrumentation

5 Results and Discussion

This paper presents the results of drained compression triaxial tests conducted on unreinforced river debris material at a confining pressure of 50 kPa. The testing protocol involved initial isotropic consolidation, alternating monotonic loading, and unloading cycles. The purpose of the tests was to evaluate the stress-strain response with monotonic loading and unloading events. During Stage 1, the specimens were isotopically consolidated to a confining pressure of 50 kPa. In the next stage, monotonic loading was applied to a deviatoric stress of 5 kPa, interspersed with unloading loading. Similarly, each stage (deviatoric stresses: 25kPa, 37.5kPa, 50kPa, 75kPa, 100kPa) was followed by unloading to zero deviatoric stress and subsequent reloading. Finally, the specimen was subjected to monotonic loading to failure.

Stress-strain responses from external strain measurements at the top surface were recorded for unreinforced and reinforced soil samples during different loading and reloading stages, as shown in Figs. 6(a–c) and 6(d–f), respectively. The reinforced soil exhibited a final yield stress of 550 kPa, approximately twice that of the unreinforced soil (250 kPa). Accordingly, Fig. 7(a) and Fig. 7(b) present the failure modes of the unreinforced and reinforced soil specimens, respectively, at the end of the final loading stage. The figures indicate that the unreinforced specimen exhibited shear failure, while the reinforced specimen showed bulging between the geogrid layers. This bulging behavior contributed to an increased final failure load in the reinforced case. As illustrated in Figs. 8(a–c), the bottom geogrid experienced a strain of 0.3% when bulging was initiated, with no rib failure observed throughout the final loading stage. Additionally, the stress-strain curves derived from local strain measurements were analysed to illustrate the local behavior of the specimen during testing, as depicted in Figs. 9(a-f) for unreinforced and unreinforced soil specimens. The reference results presented here will be repeated for further tests with different confining pressures and reinforced material to evaluate the performance of this material for use in bridge abutments, such as shear strength behavior, cyclic loading behavior, and deformation characteristics.

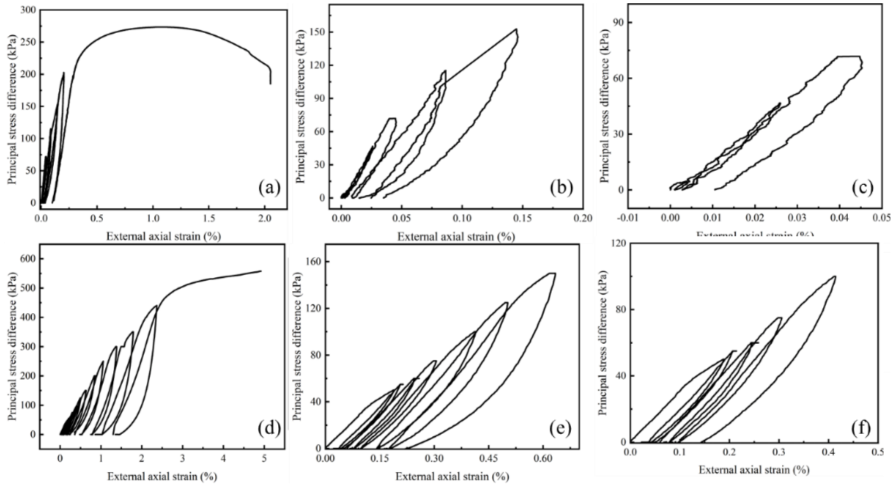

Fig. 6. (a) Overall external axial stress-strain relationship of unreinforced soil, **(b)** close-up view of loading and unloading curves of unreinforced soil until 150kPa **(c)** close up view of loading and unloading curves of unreinforced soil until 100kPa, **(d)** Overall external axial stress-strain relationship of reinforced soil, **(b)** close-up view of loading and unloading curves of reinforced soil until 150kPa **(c)** close up view of loading and unloading curves of reinforced soil until 100kPa

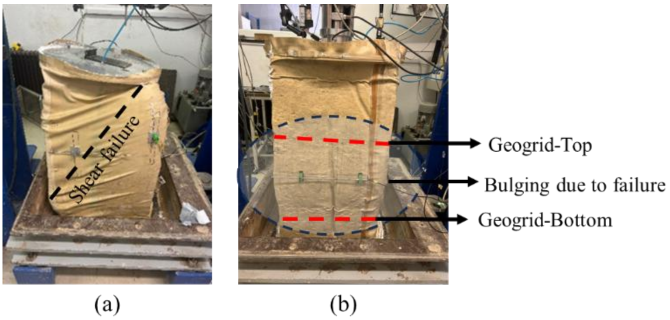

Fig. 7. **(a)** Unreinforced triaxial specimen after failure, **(b)** Reinforced triaxial Triaxial specimen after failure

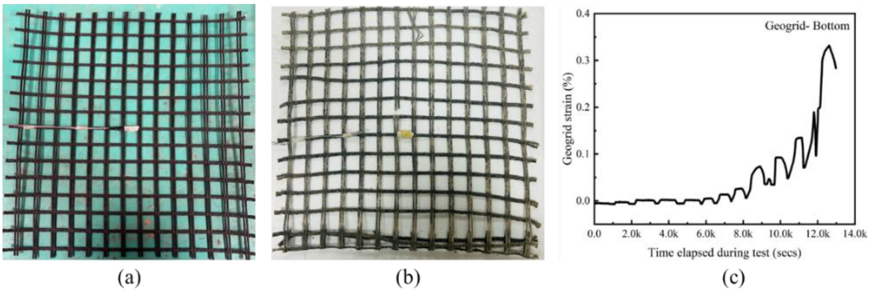

Fig. 8. **(a)** Bottom geogrid during sample preparation, **(b)** Bottom geogrid after the triaxial test, **(c)** Geogrid train evolution during the test

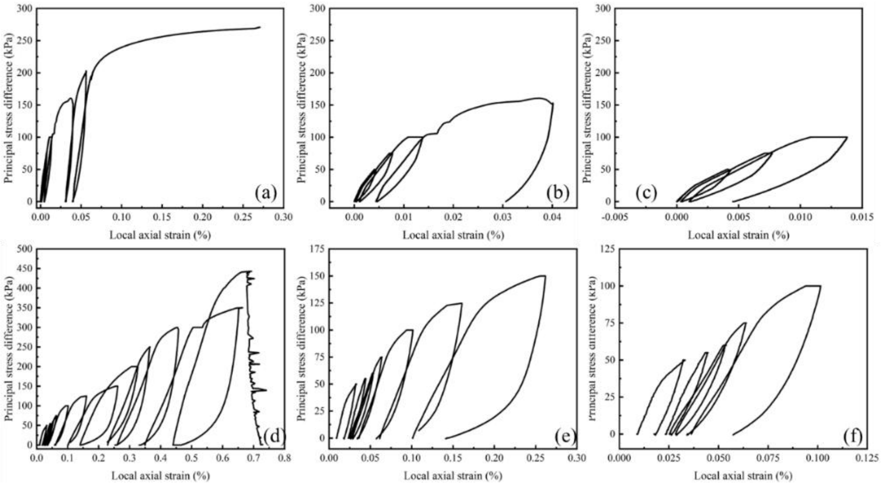

Fig. 9. **(a)** Overall local axial stress-strain relationship of unreinforced soil, **(b)** close-up view of loading and unloading curves of unreinforced soil until 150kPa, **(c)** close-up view of loading and unloading curves until of unreinforced soil 100kPa, **(d)** Overall local axial stress-strain relationship of reinforced soil, **(d)** close-up view of loading and unloading curves of reinforced soil until 150kPa, **(f)** close-up view of loading and unloading of reinforced soil curves until 100kPa

6 Conclusions and Future Scope

The innovative integration of semi-full-height rigid facings with geosynthetic reinforcements offers a cost-efficient and resilient design solution for bridge abutments while reducing the need for traditional anti-erosion measures. This study highlights the feasibility and potential of using river debris as a sustainable backfill material for these FHR-GRS bridge abutments, addressing environmental and economic challenges in infrastructure development. The preliminary results indicate that River debris, primarily classified as well-graded gravel (GW) with a high gravel content (69.3%) and limited fines (<5%), meets the required compaction and density standards (95% of 2.35 g/cm³ dry density, with an optimum moisture content of 6.8%). The large-scale test apparatus, developed at ZAG, was instrumental in testing large-scale samples to evaluate the mechanical performance of the river debris material. Drained triaxial tests conducted under a confining pressure of 50 kPa showed consistent stress–strain responses. The observed variations indicate improved deformation characteristics for the reinforced soil samples in comparison to the unreinforced soil. Subsequent testing will focus on reinforced river debris under varying confining pressures (e.g., 50 and 25 kPa). The planned scope of future research includes analysing shear strength, cyclic loading response, and deformation properties to enhance the GRS bridge abutment design and execute its construction in the field with modifications using river debris and geogrid reinforcements.

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