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Potential for Use of Recycled Waste Materials in Gravel Drains for Liquefaction Mitigation: A Review

S. Sarangi[1], R. Ayothiraman[2], and M. Datta[3]

[1]Research Scholar, Indian Institute of Technology Delhi, New Delhi, India, email: sarangi94@gmail.com

[2]Professor, Indian Institute of Technology Delhi, New Delhi, India, email: araman@iitd.ac.in

[3]Professor, Indian Institute of Technology Delhi, New Delhi, India, email: mdatta@iitd.ac.in

ABSTRACT

Gravel drains are used as a liquefaction mitigation method which works by providing a shorter path for faster dissipation of excess porewater pressure generated during earthquake shaking. These drains are made of conventional aggregates such as crushed stone and gravel. This paper reviews the material characteristics of four different waste materials - recycled Construction & Demolition (C & D) waste (Recycled Concrete Aggregate - RCA type), recycled C & D waste (Mixed Recycled Aggregate - MRA type), Tyre-Derived Aggregates (TDA), and Bottom Ash (BA) from waste-to-energy (WtE) plants with an objective to assess their suitability as an alternative to natural aggregates (NA) in gravel drains. The data available from literature reveals that RCA has properties satisfactory for its reuse in gravel drains. Further studies need to be conducted on MRA and TDA to understand the feasibility of their reuse in gravel drains. BA from WtE plants, owing to its gravel content of less than 30%, is unsuitable for gravel drain applications unless processed further.

Keywords: liquefaction, gravel drains, tyre chips, C & D waste, waste-to-energy bottom ash

1 INTRODUCTION

The effects of earthquake-induced liquefaction can be minimized by changing the characteristics or response of the liquefiable soil deposit. Methods which involve deep compaction and vibratory techniques to strengthen the soil are difficult to employ when working at sites with previous developments. One potential ground improvement method against liquefaction without causing any disturbance to the soil or the nearby structures is accelerated drainage through in-situ vertical drains (e.g., gravel drains, prefabricated earthquake drains). They expedite the dissipation of excess porewater pressure by reducing the drainage path length. Gravel drains typically utilise NA such as gravel and crushed stone. However, to achieve environmental sustainability, there is a need to reduce the dependence on natural materials and shift towards sustainable alternatives. There is only a limited number of studies exploring the potential to replace aggregates in gravel drains with alternate materials. Considering the world has been grappling with the issue of waste management, there exist ample opportunities to look at waste materials that can replace aggregates in various applications - gravel drains being one of them. This approach comes with dual benefits: (a) reducing demand for natural resources and associated environmental impact and (b) reducing the disposal of waste materials to landfills. This paper reviews the literature on gravel drains to understand the state-of-the-art in this method and on the material characteristics of RCA, MRA, TDA, and BA from WtE plants with an objective to identify the critical aspects related to its reuse in gravel drains for liquefaction mitigation.

2 CONVENTIONAL GRAVEL DRAINS

Gravel drains are vertical drains of diameter 400 to 800 mm and depth of 3 to 20 m made of NA. An analytical method to evaluate the effect of radial drainage through drain wells was first proposed by Seed & Booker (1977). The proposed method assumed the drain wells offered no resistance to flow i.e., they have infinite permeability. According to the authors, the drains perform efficiently under earthquake load, provided it has a permeability of the order of two hundred times that of the liquefiable sand layer.

Several studies have attempted to verify the design procedure proposed by Seed & Booker through laboratory model tests, including large-scale 1-*g* model tests (Sasaki & Taniguchi, 1982; Iai et al., 1988), small-scale 1-*g* model tests (Matsubara et al., 1988; Bouckovalas et al., 2009), centrifuge tests (Kimura et al., 1995; Garcia-Torezz & Madabhushi, 2018; Badanagki et al., 2019), and field test (Onoue et al., 1987). Sasaki & Taniguchi (1982) and Iai et al. (1988) conducted large-scale 1-*g* shaking table tests to study the effects of gravel drains on preventing the liquefaction of sandy soils. Iai et al. (1988) observed that the porewater pressure ratio depends on the well-resistance offered by the gravel drain i.e., the assumption of infinite permeability for drains is not accurate. Matsubara et al. (1988) developed a finite element program to incorporate the effect of well-resistance in the design and verified this modified design using shaking table tests. A few studies (Ohkita et al., 1986; Onoue, 1988) also tried to modify the design charts proposed by Seed & Booker to incorporate the effects of well-resistance. Onoue et al. (1987) performed in-situ experiments to quantify the effects of well-resistance on the efficiency of gravel drains. After verifying their equation's validity by comparing the predicted values and the actual measurements, Onoue (1988) developed a detailed design procedure, and design diagrams for reading the most suitable spacing for gravel drains for wide ranges of design pore pressure ratios, cycle ratios, and coefficients of well-resistance. Further, Yoshimi & Tokimatsu (1991) provided a basis for selecting a dimensionless time factor (T_d) for a ductile design in case the ground is subject to an earthquake stronger than the design earthquake. Pestana et al. (1998) analysed the development of excess pore pressure in a layered soil profile, accounting for vertical and horizontal drainage with a non-constant 'equivalent hydraulic conductivity', head losses due to horizontal flow into the drain, and the presence of a reservoir directly connected to the drain. A comparison of the porewater pressure ratios calculated using various methods is shown in Figure 1. Seed & Booker's approach with the modifications as recommended by some of these studies are still in practice even after 40 years and are also adopted by several contemporary design handbooks and guidelines (USACE 1999; INA 2001, etc.).

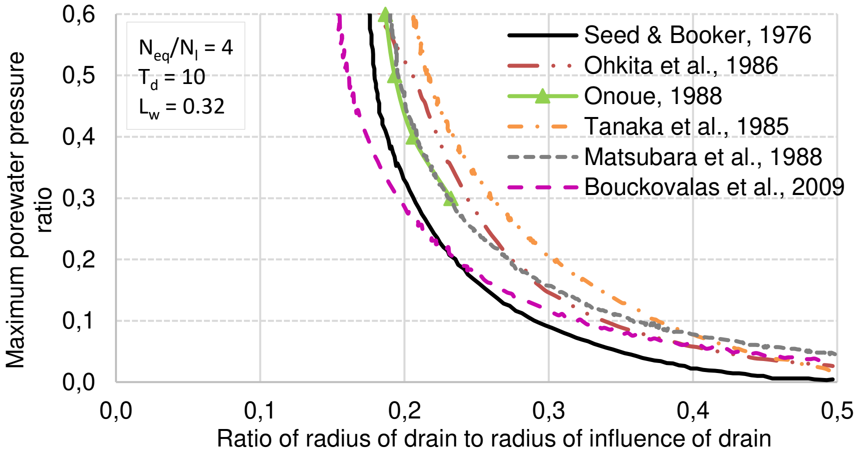

Figure 1. *Comparison of results calculated by several methods* *(N_{eq}: Equivalent number of cycles corresponding to the earthquake magnitude; N_l: number of cycles required to reach 100% excess pore water pressure ratio; T_d: Dimensionless time factor; L_w: Coefficient of well resistance)*

Considerable research has focused on the applicability of vertical drains for specific structures such as half-buried type roads (Sasaki & Taniguchi, 1982), oil tanks (Kimura et al., 1995), shallow foundations (Garcia-Torres & Madabhushi, 2018; Badanagki et al., 2019), and underground structures (Mahmoud et al., 2020). Sasaki & Taniguchi (1982) conducted 1-*g* model tests on half-buried type roads with and without gravel drains and concluded that gravel drains could prevent liquefaction of the sand around buried and half-buried type structures. Kimura et al. (1995) performed a series of centrifuge tests with a tank resting on the surface and a tunnel below the sand deposit. The magnitude of excess porewater pressures and settlement of the tank was reduced by 70% by the placement of gravel drains around its perimeter. However, a single row of gravel drains could not prevent the triggering of liquefaction below the tunnel even though the heave was reduced by half. Garcia-Torres & Madabhushi (2018) conducted centrifuge model tests to understand the behaviour of soil with and without gravel drains under a shallow foundation. As expected, the sand bed with drains showed a lower rate of excess porewater pressure generation and lesser settlement of the foundation. However, the settlement couldn't be fully avoided as vertical drains lost stability due to free-field liquefied soil. Badanagki et al. (2019) conducted a series of centrifuge model tests to evaluate the performance of gravel drains in sites with a non-uniform liquefiable layer with a shallow-founded 3-storey model structure. The net foundation settlements, rotations, and lateral displacements could be reduced by the presence of drains. However, the seismic demands on the foundation and superstructure increased. Mahmoud et al. (2020) studied the effects of using gravel drains and a combination of mitigation methods on the uplift of underground structures in saturated liquefiable soil during an earthquake, using an energy-based model through FLAC. The combination of gravel drains with impermeable base mitigation was found to be more efficient against the uplift of underground structures due to liquefaction.

Japan has employed gravel drains as a liquefaction countermeasure extensively since the 1990s. Iai et al. (1994) surveyed the effects of the 1993 Kushiro-Oki earthquake on the Port of Kushiro, including the recorded earthquake motions, the ground conditions, and the results of the in-situ examination of gravel drains after the earthquake. Orense et al. (2012) studied the effects of the 2011 off the Pacific coast of Tohoku Earthquake on the Tokyo Bay area located about 400 km from the epicentre and reported extensive liquefaction across areas except at locations which had employed liquefaction countermeasures such as gravel drains and sand compaction piles. During the 1995 Hyoguke-Nanbu earthquake, the Kobe Port of Japan witnessed widespread liquefaction-related damages. Soga (1998) reported that gravel drains were employed at the port as liquefaction countermeasures after this. These case studies are summarised in Table 1. Since the 1995 Kobe earthquake, stronger design earthquakes (of high intensity and low probability of occurrence during the lifetime of a structure) are commonly being stipulated in Japan. Hence, the low spacing determined from the current design procedure made this method less popular. However, there are sites where liquefaction countermeasures with gravel drains have been implemented following the design procedure and were not affected by soil liquefaction even when earthquakes of ground motions stronger than the design earthquake hit the sites (Yasuda et al., 1996; Unno et al., 2014).

Table 1. *Summary of case studies*

Case	Soil Strata	Drain Specs.	Remarks
Port of Kushiro (Iai et al., 1994)	Loose sand fill of 6 to 10 m depth resting over medium dense to dense cohesionless soil.	400 mm dia.; 5 m spacing	Satisfactory performance during 1993 Kushiro-Oki EQ
Tokyo Bay Area (Orense et al., 2012)	Reclaimed and filled layers, underlain by alluvial sand, clay; poor SPT-N values throughout	400 mm dia.; 2.6 m x 1.3 m grid	Satisfactory performance during 2011 off the Pacific coast of Tohoku EQ
Kobe Port (Soga, 1998)	Loose saturated sandy fills, uncompacted, underlain by alluvial clay and dense sand	400 mm dia.; 1.5 m spacing	No reports on performance after a real EQ event.

3 NEED FOR ALTERNATE MATERIALS

Conventionally, natural gravel and crushed stones are used as gravel drain material. However, in recent years, the use and demand for NA have increased significantly in India due to rapid urbanisation, growth in the infrastructure sector, smart cities mission etc. The demand for aggregates will continue to increase, maintaining an unsustainable path unless suitable alternatives are explored. The NA produced in the United States, and Europe in the past 10 years are shown in Figure 2. In the US in 2021, nearly 90% of the NA produced was consumed by the construction industry (Mineral Commodities Summaries, 2022).

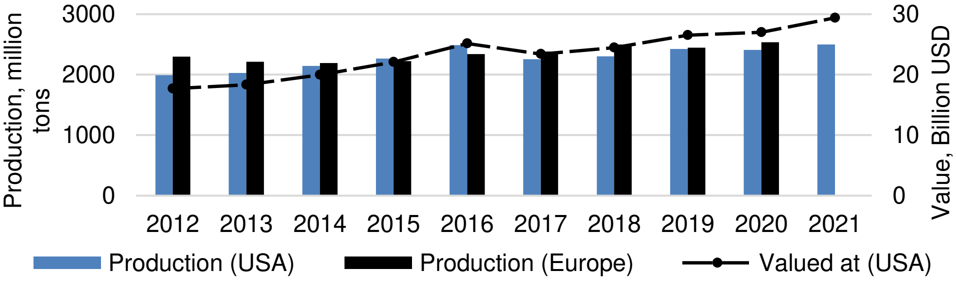

Figure 2. *Crushed Stone and Construction Sand & Gravel produced in the US and Europe from 2012-2021(Mineral Commodities Summaries 2013-22; World Mineral Production 2012-2020)*

In India, the demand for crushed stone in 2020 was somewhere around 5000 million tons. Thus, an excellent opportunity exists worldwide for significant sustainability gains to be made through the increased use of alternative materials.

4 RECYCLED WASTE MATERIALS

As a part of the global move towards sustainability, extensive research has been done to make the civil engineering industry more sustainable. Researchers have looked at the possibility of replacing NA in plain and reinforced concrete with recycled C & D waste aggregates, and they are already used in various civil engineering applications. Various design codes now provide guidelines for using RCA in concrete (e.g., BS EN 12620–2013; IS 383–2016). The IS 383 has recommendations for using other waste materials such as iron, steel, and copper slag as well. Studies reported by Safan et al. (2017), Awan et al. (2021), etc. analysed the performance of Tyre Derived Aggregates (TDA) of various gradations as aggregates in concrete. The IRC 121–2017 gives detailed guidelines for using C & D waste in the road sector. Studies have examined liquefaction prevention using tyre-sand mixes and earth pressure reduction using tyre chips in backfill (Hazarika & Yasuhara, 2007). A few studies investigated the possibility of replacing stone column aggregates with waste materials (Ayothiraman & Soumya, 2015; Mazumdar et al., 2018; Mazumder & Ayothiraman, 2021). There are a limited number of studies (Orense et al., 2003; Bahadori et al., 2018; Garcia-Torres & Madabhushi, 2019) reported in literature where an attempt has been made to study the effects of replacing gravel with alternate materials in gravel drains to mitigate liquefaction. All available studies have shown positive results for waste material drains and point towards the need to explore these options further.

4.1 Construction & Demolition waste

Globally, cities generate about 2.01 billion tons of solid waste per year, half of which can be characterised as C & D waste, according to a 2018 report on solid waste by the World Bank. The global data for C & D waste generated by various nations in 2013-14, and the typical composition of C & D waste in India as reported by Technology Information, Forecasting and Assessment Council, 2001 is shown in Figure 3. Numerous factors affect the C & D waste generation such as population, rate of urbanisation, population density and socio-economic status of people, age of the city and construction and demolition patterns/practices.

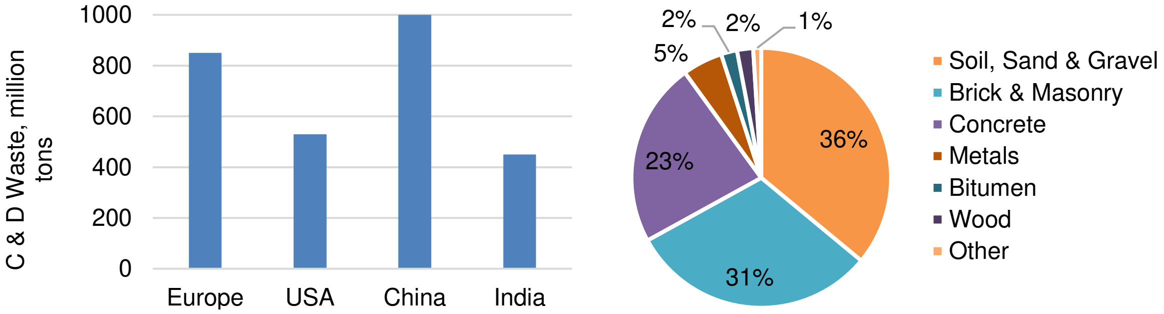

Figure 3. *C & D waste generated globally in 2013-14 (left). C&D Waste Composition- Urban India (right)*

The properties of recycled C & D wastes depend on their composition. C & D waste with higher amounts of NA display properties closer to that of NA. As the amount of cement mortar increases, they exhibit more inferior properties owing to their porous nature and low density. Masonry materials are more porous and less dense than cement mortar. Thus, their presence makes the material further inferior. However, the presence of less porous materials like sanitary wares can improve the property of the recycled aggregates. It has been observed that the properties of RCA depend on the strength of the original concrete and the quality of the NA used in the concrete (Dhir & Paine, 2003; Gokce et al., 2011). MRA also exhibits similar behaviour – the higher the compressive strength of the original brick unit and the lower the brick content, the superior the properties of MRA (Barbudo et al., 2012; Jiménez et al., 2011). Most of the RCA and MRA samples could be classified as ‘poorly graded gravel’ based on ASTM D2487–2006 (Dhir et al., 2019). RCA which is composed of crushed concrete is generally slightly inferior to NA in terms of density, specific gravity, crushing strength, and flakiness. MRA contains both crushed concrete and masonry waste which makes it further inferior with respect to these properties.

The use of RCA in geotechnical engineering applications is not likely to give rise to a significant environmental hazard unless contaminated. However, it is 'slightly alkaline' to 'alkaline' in composition (pH 7.5 to 11), due to residual cement paste content, compared to NA which has a neutral pH. The presence of foreign materials, if not checked while sorting, can cause contamination. Barbudo et al. (2012) and Galvin et al. (2013) conducted chemical leachate analyses on RCA and MRA for the release of hazardous elements, such as Ba, Cr, Cu, Mo, Ni, Sb, Se, and Zn. The concentration of all elements released fell below waste acceptance criteria levels for inert waste in the United Kingdom, except for a few samples, which had a high Cr level. Dhir et al. (2019) suggested that issue of Cr can be avoided if proper sorting of waste is ensured before processing. However, as such there are no established process of sorting to remove Cr (VI) and the choice of whether to use the material in drainage applications can be made only after proper leachate studies.

4.2 Tyre-Derived Aggregates

Scrap tyre is a major source of waste across the world. Global trade in waste tyres has more than doubled in the past decade, mainly to developing countries like India and Malaysia. In most countries, including China and the United States, most scrap tyres are handled domestically and dumped in landfills, recycled, or used as fuel in cement and paper factories.

ASTM D6270–20 gives the standard practice for use of scrap tyres in civil engineering applications and their material characterisation. Reddy & Marella (2001) and Mohajerani et al. (2020) have consolidated the geotechnical properties for TDA as available in the literature. Mohajerani et al. (2020) suggest that the positive elastic features of rubber can often improve some of the characteristics of the soil when TDA is used in combination with sand. However, further studies are recommended in this regard. Several laboratory and field studies have been conducted to understand the effects on surrounding soil and groundwater while using TDA in geotechnical engineering applications. Downs et al. (1996) conducted Toxicity Characteristics Leaching Procedure (TCLP) which gives an indication of potential pollutants that may leach from the waste, showed that tyre shreds are not hazardous to human health. The authors confirmed that no primary drinking water standards are exceeded due to tyre leachate. However, it was reported that secondary standards for Zinc and Manganese might exceed. Nelson & Mueller (1994) and Gualtieri et al. (2005) also confirmed the leaching of Zinc. Azizian et al. (2003) studied the leaching behaviour of crumb rubber asphalt concrete and observed that concentrations of Mercury and Aluminium exceeded the toxic concentrations for the aquatic toxicity tests, and, therefore, can potentially be harmful. At low pH, metals are leached most readily, and organics are leached most readily at high pH. Thus, using TDA in environments with a near-neutral pH is preferable. When used above the water table, they do not cause the primary drinking water standards for metals to be exceeded whereas, when placed below, a negligible off-site effect on water quality can be expected (ASTM D6270).

4.3 Bottom Ash from Waste-to-Energy plants

WtE plants incinerate Municipal Solid Waste to generate energy. Although this technology is a step towards sustainability, it generates vast amounts of BA and Fly Ash (FA) that ends up in landfills and waste dumps making the efforts towards sustainability futile.

The nature of the by-products of WtE incineration plants depends on the raw waste that goes into the incinerator, operational conditions of the plant such as the type of furnace, its capacity, temperature maintained etc, and the methods employed to collect these by-products. Margallo et al. (2015) reported that about 200 to 300 kg of BA is obtained for every ton of waste burnt. BA mostly consists of non-combustible materials like glass, ceramics, unburned matter, and organic carbon. The pH of BA ranges from 10.5 to 12.2. The loss on ignition (LOI) of BA depends on the efficiency of the employed incineration process and varies between 1.9% and 6.3%. Modern WtE plants which facilitate proper incineration result in an LOI of less than 3%, indicative of satisfactory burnout (Chandler et al., 1997). A specific gravity of around 2.2 has been reported in the literature. Los Angeles abrasion value of around 43% was also reported (Lynn et al., 2016). Gupta et al. (2021) assessed the feasibility of the beneficial reuse of BA produced from two different WtE plants in Delhi, India. It was observed that 20 to 25% of the material was gravelly. A high presence of organics, total dissolved solids, sulphates, and chlorides was also observed. However, the European Waste Catalogue (EWC) classifies BA under the non-hazardous category and as per CPCB, India, 2020, the concentration of various heavy metals (As, Cd, Cr, Mn, Pb, Se, Cu, Ni, Zn, Co, V, Sb) in WtE BA was found to be less than the concentration limits to categorise it as hazardous waste as per the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016.

5 SUMMARY

Studies available in the literature for gravel drains from 1977 to 2022 were reviewed. The reviewed literature included laboratory model studies, case studies, analytical/numerical studies, and a field study. However, only three studies have explored the potential to replace aggregates in columnar gravel drains with alternate materials. Thus, a need for research focusing on alternate options for gravel drain material is observed. The following observations are made from the review of existing literature on RCA, MRA, TDA, and BA from WtE incinerators.

1. Literature pertaining to the characterisation of C & D waste for applications in fills, pavement subgrades, plain and reinforced concrete, stone columns, gravel drains etc. was reviewed. It could be concluded that C & D waste (RCA type) which is composed of crushed concrete is closer to conventional aggregates in terms of gradation, specific gravity, and drainage and crushing properties. MRA type C & D waste contains brickbats which are prone to crushing during construction and that require further study.

2. Tyre waste is a material whose civil engineering applications are still mostly in the research stage except for pavement-related applications. They can be shredded into varied sizes and gradations based on the requirement. Leaching studies on tyre wastes have deemed them not toxic and concluded that they do not affect the primary drinking water standards. However, the influence of low stiffness of the tyre particles on response during earthquakes requires further study.

3. The BA from WtE incineration plants is composed of coarse-grained particles. However, gravel-sized particles make up less than 30%. Hence, it is unsuitable as aggregates in gravel drains without further segregation.

Thus, RCA type C & D waste has an excellent potential to be used as aggregates in gravel drains. The feasibility of using MRA and TDA in gravel drains needs rigorous investigation.

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