

# Constructing structures on backfilled opencast mine spoil for better sustainability

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**In this study we collate existing knowledge and suggest a possible methodology for construction on environmentally challenged backfilled mines to restore the sustainability of human settlement. The possibility of reconstruction on a backfill soil with a sustainable solution has been explored. The study highlights the issue of subsidence in backfilled opencast mines through a meticulous understanding of different case studies of construction on mine spoil. The prime focus of the study apart from structural and construction aspects includes the behaviour of heterogeneous mine spoil. Collapse settlement and hydrocompression are discussed to develop an understanding of failure in backfill. The study also incorporates the proposition of possible effective ground improvement treatment for improving soil behaviour through effective utilization of demolished concrete waste material. Further, ground improvement through demolished waste stone column has also been discussed. Finally, a feasible method for constructing a low-rise building on backfilled soil is proposed with available experimental data on bearing capacity. This study along with a comprehensive list of references may prove useful for conducting further research and a thorough understanding of the issues faced by the mining sector in India and other developing countries.**

**Keywords:** Opencast mines, backfill soil, collapse settlement, hydrocompression, sustainability.

ACCORDING to a recent report, there is a direct relationship between population growth and energy resources<sup>1</sup>. The approximate area of the world under mining between 1976 and 2000 was about 37,000 sq. km, which covers about 0.2% of the total available land surface on earth<sup>2</sup>. The consequence as per studies<sup>3</sup> includes challenges for the existing human settlements, landscape, ecological imbalance and other environmental issues<sup>3</sup>. The situation may be critical in future because of the population outburst in countries like India, China, etc.<sup>1-3</sup>. Thus, sustainable solution of developing housing on filled-up waste land is the need of the hour. Further, rehabilitation on such challenged waste land is a difficult task which requires incorporation of technical knowledge in areas of structure and geotechnical engineering.

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Singh<sup>4</sup> describes the process of opencast mining to be utilized when deposits of commercially useful minerals or rocks are found at a shallow depth of 30–60 m from the surface. A report<sup>5</sup> on sustainable development programme of mining mentions that during a mining operation, human settlements are displaced and their rehabilitation becomes an important issue to the mining agency from the point of view of ecological balance, socio-economic and human satisfaction<sup>5</sup>. Few studies also mention about systematic filling of the opencast pit with mine spoil<sup>6,7</sup>. Such systematic filling of the opencast pit is productive as the area can be effectively utilized for commercial purposes.

At present, only few attempts have been made for constructing such structures, but they were unsuccessful. Most of the failure happened due to settlement of the backfill material. In this context, it is a technical challenge to develop an adequate methodology for ground improvement on such land filled with mine spoils, which can be utilized for constructing buildings. Another crucial issue in this regard is to develop structures with suitable foundation having features of arresting differential settlements. Thus, in particular, consideration of integrated behaviour of soil–foundation–structure system is necessary.

Relatively very limited effort has been directed in this particular domain, as countries with low population density do not face this severe problem. In this context, the present article summarizes the existing research outcome in this particular direction collating the information and concepts available from the literature. This will enable researchers in the field to identify the gaps and propose a complete set of guidelines for achieving the above-mentioned goal. Thus, the focus is also to consider the possibility of how a low-rise structure with adequate ground improvement technique may safely stand on such backfill. This will also help make the mining activities in India and other populated countries sustainable from the point of view of the built environment. Such a requirement is being emphasized by the Ministry of Coal, Government of India through various initiatives, e.g. the present study.

## Characterization of backfill soil

Bowels<sup>8</sup> describes how soils can be characterized by various properties like their soil particle size and shape,

degree of roundness, surface texture, colour and composition. Further, different index properties of the soil like liquid limit, plastic limit, shrinkage limit, plasticity index, liquidity index and consistency index also play a vital role to characterize soil deposits and predict their short-term as well as long-term behaviour under loading. The literature<sup>9-13</sup> on fill soil in opencast coal mines describes that, in general, soils consist of sandstone, siltstone, mudstone, shale, clay and coal<sup>9-13</sup>.

The grain size distribution of soil categorizes it into two parts, i.e. well-graded and poorly graded soil, and this plays a significant role in proper compaction of soil<sup>8</sup>. Studies<sup>14</sup> on fill soil describe heterogeneity as the cause for its collapse settlement<sup>14</sup>. The large-sized particles result in improper compaction and additional voids, which on saturation with water leads to collapse settlement.

An experimental study on backfill of depth 32 m describes the percentage settlement and time graph, which show that significant subsidence of the fill happened during the early filling period<sup>15</sup>. The study also describes different grades of oversized particles in the range 0–20%, 20–40%, 40–70% and 70–100%, and their contribution to compaction<sup>15</sup>. In the broad range of 0–40% oversized particles, their compaction is negligible<sup>16</sup>. While the effect of the oversized particle is significant in compaction and settlement in the broad range 40–100% (ref. 16).

A plate load test carried out on different ages of backfill preloaded due to its natural conditioning reports a safe bearing pressure of about 200 kN/m<sup>2</sup> with settlement less than 25 mm (ref. 17). In another study, preloading of the site with surcharge to a depth of 7 m for improving bearing capacity was followed<sup>18</sup>. The plate load test of such a study shows maximum deflection at the corresponding stress of 80 and 160 kN/m<sup>2</sup> as 6.8 mm and 17 mm respectively<sup>18</sup>, which clearly does not exceed the safe limit of 25 mm. However, such a bearing capacity was attained with time as well as by following a ground improvement process. These results show that construction of 2–3 storey buildings on such backfilled soils is possible, with adequate measures. However, for better sustainability and greater safety, surface compaction of few metres depth and an effective ground improvement method should be incorporated.

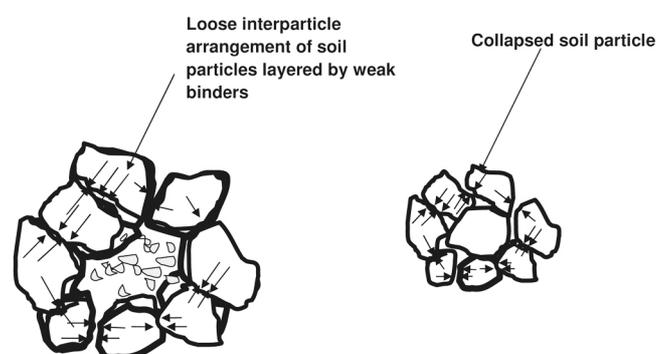
### State-of-the-art on subsidence of backfill

The case studies available on mine spoils point out the reasons behind structural settlement based on failure and present aspects like characteristics of backfill soil<sup>19-21</sup>, available moisture content<sup>10,21,22</sup>, applied building load<sup>19</sup> and time-bound creep<sup>11,12,19,21</sup>.

The prime reason for settlement on structures in fill soil is due to increase in the moisture content of the soil.

This may be an outcome of fluctuation in groundwater table, precipitation, ingress of water from flooded surface or near-surface construction such as drainage trenches or reduction in shear strength of the soil by any means. A study on subsidence of backfill indicates that compacted clayey sands and sandy clays due to wetting or hydro-compression show large settlement when subjected to loading<sup>23</sup>. Soils having a loose configuration or those with low *in situ* bulk density are generally prone to hydrocompression or collapse settlement<sup>9</sup>. Figure 1 shows the mechanism of collapse compression where the particles are bonded together by loose interparticle bonding with poor binder gap between them. Further, as the particle comes in contact with water, cohesive soil layer gets dissolved causing the particle to slide leading to collapse. As the interparticle binders are lost or softened, the larger particles are free to slide further leading to collapse on themselves. Studies<sup>24</sup> on two sites in Canada showed that the process of groundwater recharge can lead to a settlement of 4% due to hydrocompression<sup>24</sup>. Also, soils with low plasticity in spoil tend to experience slightly more hydrocompression than non-plastic mine spoil soils, and hydrocompression tends to increase slightly with increasing confining stress<sup>25</sup>. The results of the same study show that the mine spoil soils with dry density,  $\gamma_d$  greater than 19 kN/m<sup>3</sup> expand by only 1%; while those with  $\gamma_d$  below 19 kN/m<sup>3</sup> show significant loss in volume after wetting<sup>25</sup>. However, this issue needs further detailed studies at different sites before reaching any conclusion.

Soil mixtures of clayey sand and sandy clay are reported to be most susceptible to hydrocompression<sup>23,26</sup>. Soils such as silty sand, sandy silts and clayey sand in arid and semiarid regions are generally subjected to collapse upon saturation. The loose bulky arrangement of the soil particles is the main reason for collapse potential of the soil and commonly has low *in situ* bulk density. The potential of the site to collapse also depends on inundation and prior applied ground treatment method for its densification. Most of the backfill failure that has



**Figure 1.** Basic mechanism behind collapse compression of the fill soil.

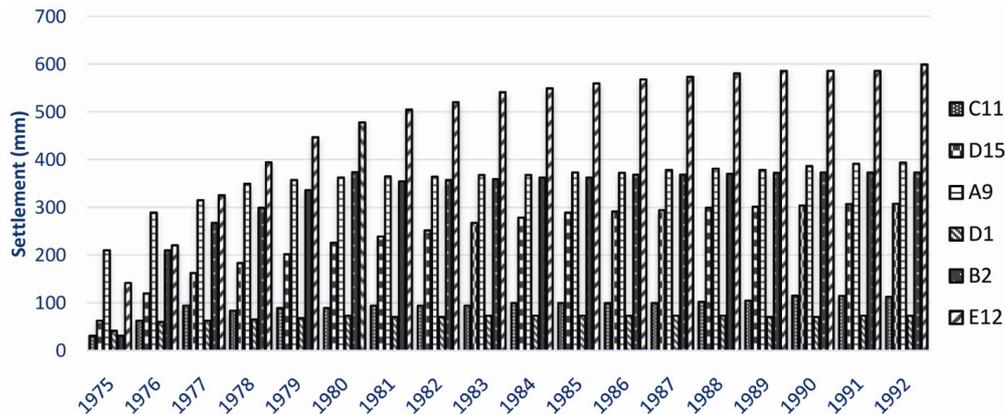


Figure 2. Approximate settlement of different gauge points at Horsley during different years<sup>9,27-29</sup>.

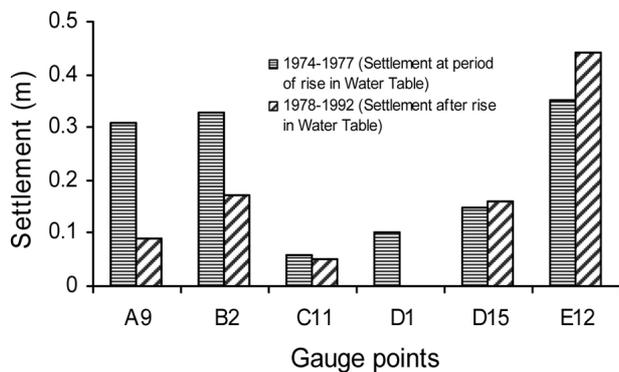


Figure 3. Comparison between settlement during rise in water table and that in later years<sup>9,27-29</sup>.

happened earlier is mainly due to the increase in moisture content of the soil that has ultimately led to collapse settlement of backfill. So construction on slightly elevated ground may help to drain out the surface water. However, prior inundation of the site with water may also allow the soil to collapse before construction.

**Horsley opencast backfill:** A case study on backfilled mine was carried out between 1961 and 1970 at Horsley mining site, near Newcastle, UK<sup>9,27-30</sup>. The backfill, in general, comprises of mudstone, and sandstone, with dominance of the former. The backfill settlement was monitored for 19 years starting from 1973 after restoration. Figure 2 presents the analysed works by different researchers and shows the detailed behaviour of movement in backfill from 1975 to 1992. The effect of water table came into focus in 1974, when it reached a new equilibrium level as the pumping out of groundwater had stopped at the backfill site. The rate of settlement was very high during the period 1974–1977 with rise in the water table. However, after the collapse settlement of backfill, the rate of settlement has gradually reduced to a very low value. Effective settlement during the period of rising water table was very high, while the consolidation

settlement that occurred after the water table has stopped rising was less. This has been compared and presented in Figure 3 and the large difference in settlement gives an indication of collapse compression of fill soil. The degree of settlement is different at the different chosen sites due to their prior conditioning. There is negligible or almost no settlement shown by the gauge point D1 because the site has been preloaded with surcharge due to which it has been sufficiently consolidated with surcharge. On the other hand, least settlement was shown by gauge point C11 due to prior saturation with water lagoon nearby and thus had undergone subsidence well before monitoring. The oldest site A9, shows a significant amount of settlement at the time of rise in groundwater, but remains almost constant at later years of observation. Thus, it can be concluded from the above studies that rise in water table leads to rapid settlement of backfill soil. This rapid settlement of the backfill soil is primarily due to collapse settlement and when compared with creep, the rate of settlement is more in case of collapse settlement. Further, prior inundation of the site can be an effective way for allowing the soil to be collapsed before raising the site for construction, so that the future effect of settlement due to water fluctuation can be minimized.

**Hospital development on restored opencast fill:** A case study of Whitley Bay opencast coal site located in North Tyneside District, Tyne and Wear, England was carried out, where a hospital was planned to be constructed<sup>21</sup>. The work for restoration began in 1948 and was fully restored in 1952. The hospital site covered an area of about 13 ha. The fill, in general, consisted of stiff grey clay with boulders, mudstone fragments, shale and clayey sand mudstones. The hospital was situated on a flexible raft and the building, in general, consisted of load-bearing bricks. A surcharge test was conducted on trial embankments, each having an area of 20 sq. m and thickness of 2 m, 4 m and 6 m respectively. Settlements were measured using magnetic extensometer at points 2, 3, 5,

7, 10, 13 and 16 m below surface level. The inundation response of the fill for 4 m high embankment showed a significant increase in the value of collapse compression from the depth of 5–13 m, because of the small values of standard penetration test. The building showed a maximum settlement of 138 mm, which is difficult to be accommodated by any structure. The reason for the settlement as pointed out by the author<sup>21</sup> is due to the wetting-up of opencast fill. However, the study gives an idea about the advantage of raft foundation, because of which cracks were not severe and had not affected the structure as a whole. This can be an important clue for future research as well as the practical implication in this direction.

*Mine backfill at Blindwells:* Studies were carried out on opencast mine backfill at Blindwells, Scotland, UK<sup>9,31</sup>. Mining began in 1978 and was backfilled with the overburden, which comprises of mudstone, siltstone and sandstone to its maximum depth of 60 m. A continuous process of dewatering the site prior to excavation was followed in order to keep the water table below the maximum excavated depth. The site was filled and well compacted to a depth of 16 m for construction of the 1.4 km section of Tranent bypass trunk road. The required area meant for construction of pavement alone received compaction, while the other two sides of the road did not receive any systematic compaction. The projected settlement of the first 13 years showed that the area, which did not receive any compaction, settled by about 0.5 m. On the other hand, the area that received systematic compaction settled only for about 0.2 m. Prior to 1998, the rate of settlement was approximately 50 mm/year at maximum but after the rise in water table from 1998 onwards, the rate of settlement was very high, approximately 200 mm/year; almost four times. Figure 4 shows the approximate settlement of fill at four different depths of E (38 m), G (25 m), I (12 m) and K (0 m) from the surface in 12 years. From the figure, it can be clearly seen that until 1998 the creep is gradual, but with the intervention of groundwater there is significant amount of collapse settlement from the year 1998–1999 onwards.

Thus, it can be concluded from the above study of the mine backfill at Blindwells that following the regular ground compaction method up to a certain height does not sufficiently serve the purpose of controlling the settlement. As a result, there is a phenomenal change in settlement with the intervention of water. For controlling such kinds of settlement, compaction not only at the surface level but layer-wise compaction should be followed in the placement of fill. Deep ground improvement techniques can possibly be incorporated prior to construction for further control of settlement.

*Settlement on uncontrolled mine spoil fills in Eastern Kentucky:* The mine spoil fill in Eastern Kentucky,

USA was generally heterogeneous and mainly consists of earth material. The different fill materials include disposable substances such as tree stumps and root system, scrap metal, tyres, etc. A five-building motel facility was proposed for construction on mined spoil fill site in Eastern Kentucky. The architect of the proposed building appointed two geotechnical engineers for soil exploration. The first engineer after exploration of spoil fill at six different sites observed obstruction in the movement of the auger at different depths. Thus, he recommended complete removal of the fill material up to a depth of 3 m and refilling with engineered fill. The second engineer recommended removal of very limited depth of fill material. Considering cost as one of the major factors, the architect decided to adopt the recommendation of the second engineer. However, the planned structure started showing signs of failure. Cheeks<sup>13</sup> was appointed as a third party to study the reason behind the settlement of the backfill foundation. He found that water flowing in the ditch during heavy rains have entered the ground with vigour, and whirlpools were formed over the entry area. The second geotechnical engineer agreed with the 1988 evaluation of the author and accepted that the flow eroded soil-sized material (fine sand, silt and clay) from the spoils beneath the centre of building resulting in unexpected settlement. The author suggested about the incapability of both the geotechnical engineer in determining the actual depth of fill.

Thus, the consideration of the fill depth as concluded to be better and suitable by second geotechnical engineer was wrong. Author also mentions about the limited undercut methods, which limits the opportunity to detect variant conditions. This may be due to the incapability of the investigator to identify the nature of refusal material and assumption of that to be bed-rock. The misinterpretation of the data that causes auger refusal is always dangerous as it may not help to gaze the actual situation which can only be known by subsurface excavation. Thus the exploration by the author hints the importance of a rigorous spoil fill exploration if it is really very heterogeneous.

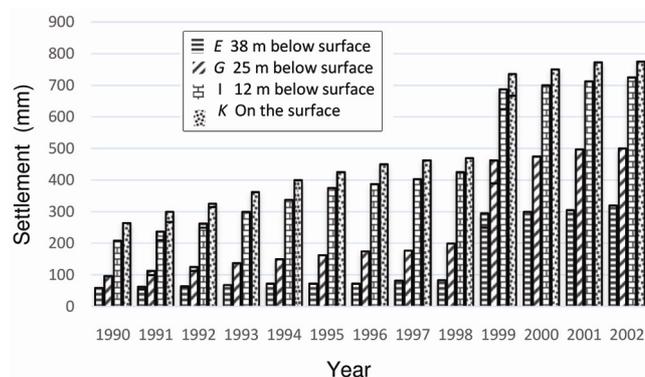


Figure 4. Approximate settlement of opencast backfill at Blindwells<sup>9</sup>.

The general method of compaction for the fill at large depth sounds illogical, as it is time as well as effort consuming. The phenomenon of collapse settlement has also led to failure of time bound consolidation fill. Consolidation also sounds unsuitable method for generating a stable backfill as this does not meet the requirement on time indeed. Thus, attention should be focused on attempts of ground improvement. A brief outline of suitable ground improvement technique is presented in the following section.

**Ground improvement**

Studies<sup>32</sup> reveal that processes like re-excavating the sites, removing the unsuitable materials and refilling the backfill to a suitable specification under strict supervision can be adopted, but probably this fails in case of deep backfill<sup>32</sup>. Further, studies also reveal that such a strict quality control is difficult to maintain in many developing countries, including India<sup>9,33</sup>. However, challenges can be adequately met by following suitable ground improvement methods depending on the site condition.

Some popular methods for ground improvement are discussed in the literature, particularly dealing with backfill<sup>9,21,34,35</sup>. The method of ground improvement on a fill soil by preloading was adopted in 24 m backfill sites<sup>34</sup>. In this study<sup>34</sup>, the fill soil was loaded with a surcharge of 7 m high within an area covering about 50 sq. m. Interestingly, the results show that most of the backfill settlement occurred at the early stage of surcharging. Thus, it was concluded that loading needs to be kept for a very short duration for collapse settlement to take place. In this context, the depth of effectiveness ( $Z_c$ ) is important. It is defined as the depth to which significant vertical compression has been produced<sup>8,9,36,37</sup>. However, the method of preloading also involves optimization in depth of effectiveness for different surcharge loading. Figure 5 is a bar diagram of backfills at different experimental sites in Snatchill<sup>9,38</sup>. The different experimental studies involve the different sites of the fill at Snatchill and their depth of effectiveness by the method of preloading. Observations show that the effect of settlement by preloading at greater depths inside the backfill is very low and thus the method has very limited depth of effectiveness. Further, from Figure 5 this can also be observed that the settlement response at different site location of Snatchill fill is different proving the fill soil to be of heterogeneous nature.

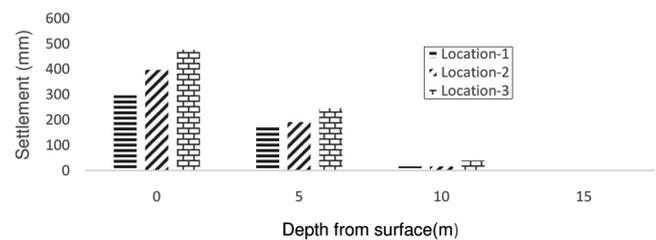
Another method for ground improvement on backfill is dynamic compaction<sup>9,37,39</sup>. The method involves dropping of heavy load from a specified height to densify the fill soil<sup>8,9,37</sup>. The process was also followed in Snatchill experimental site as well<sup>9,38</sup>, by dropping a weight of 15 tonnes, over a base area of 4 sq. m from a height of 20 m, which incorporates an average energy input of 2800 N/m<sup>2</sup>. Figure 6 shows the test results of the site at Snatchill,

where the effect of dynamic compaction at different depths with reference to surface level has been plotted for different locations. Comparison of both the methods at Snatchill experimental site is also well represented in the figure. The amount of surface settlement observed in dynamic compaction seems to be more than that for preloading. However, if the depth of effectiveness is concerned the method of preloading is significant.

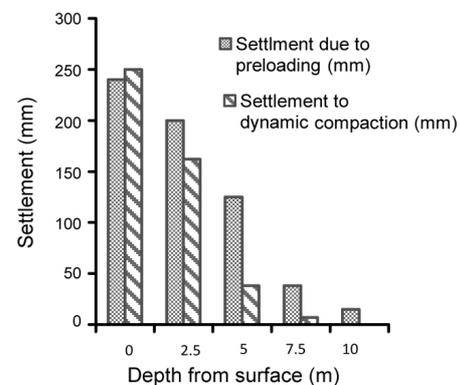
The failure due to water infiltration in Eastern Kentucky coalfield area has emphasized upon the requirement of adequate methodology for ground treatment<sup>22</sup>. Placing hydraulic barrier using geosynthetics or a geomembrane at the bottom of the excavation, as well as replacing the excavated material with a substitute that is not vulnerable to hydrocompression can be effective ways of overcoming the failure. However, sophistication, rigour as well as the cost involved may make such method prohibitive for developing countries like India.

Reinforcement of soft ground by stone columns is a well-established technique worldwide<sup>37,40-43</sup>. The technique involves substantial replacement of weak soil with a compacted vertical stone column that acts as a natural reinforcement for soil<sup>37,40-43</sup>. The superiority of this method includes increased bearing capacity, very less post-construction settlement and lateral movement of soil, upgraded slope stability, and liquefaction control.

Ballasting is also another feasible approach. This may be more economical compared to other methods. The method requires an isolated place devoid of any nearby



**Figure 5.** Approximate settlement of backfill at different depths due to preloading for different experimental studies on the same fill<sup>9,18</sup>.



**Figure 6.** Comparison between preloading and dynamic compaction<sup>9,18</sup>.

houses or a public place. The method has been gradually accepted in many developed countries and a several studies have been carried out<sup>37,44-47</sup>. The method as described through different case studies<sup>37,44-47</sup>. In general, it involves filling explosive charge through a pipe installed at the required depth and further removing the pipe before ignition<sup>37,44-47</sup>. This leads to rearrangement of soil particles to a well-compacted state and also to the formation of a borehole which can be used for the introduction of cement or fly-ash mixed slurries to act like piles. The above discussed factors are in favour of considering the method of blasting for ground improvement in opencast backfilled mine.

### Suggestions for possible construction methodology in opencast fill mines

The prime consideration before construction of any foundation or superstructure as described by Bowels<sup>8</sup>, is an appropriate ground improvement technique for making the land suitable for raising construction. The introduction of stone column can effectively reinforce the soil, and provide adequate stiffness and improve the bearing capacity. Though stone column is an effective ground improvement method, it has a drawback of failure in smearing effect due to friction<sup>37,43</sup>. However, application of this method with new materials like demolished waste can be an innovation for exploration as the rough surface of demolished waste provides adequate grip. Demolished waste is a sustainable material which has emerged as an alternative low-cost construction material with strength and durability almost comparable to regular aggregate<sup>48</sup>. Figures 7 and 8 show a broad, small-scale experimental demonstration on a loosely packed soil with an impact loading of 10 kg. The one in its natural state has greater depth of crater from impact loading, indicating less strength and stiffness. On the other hand, one with a demolished waste stone column indicates substantial improvement in strength and stiffness. The figures reveal that from the impact of load, depth of crater is less in case of the demolished waste stone column. The advan-



**Figure 7.** Broad experimental demonstration of impact loading on loose fill soil.

tage of demolished waste over regular coarse aggregate is its rough surface which upon application of loading may not fail due to smearing effect.

Introducing a sufficient number of stone columns over a depth of about 8–12 m may be useful for creating a hardened layer. This further distributes the load with lesser intensity into softer layers below as shown in Figure 9, where the reduction in intensity of stress is represented by narrower dispersion. Due to reinforcement, the soil layers become stiffer and thus act as a medium which narrows down the dispersion.

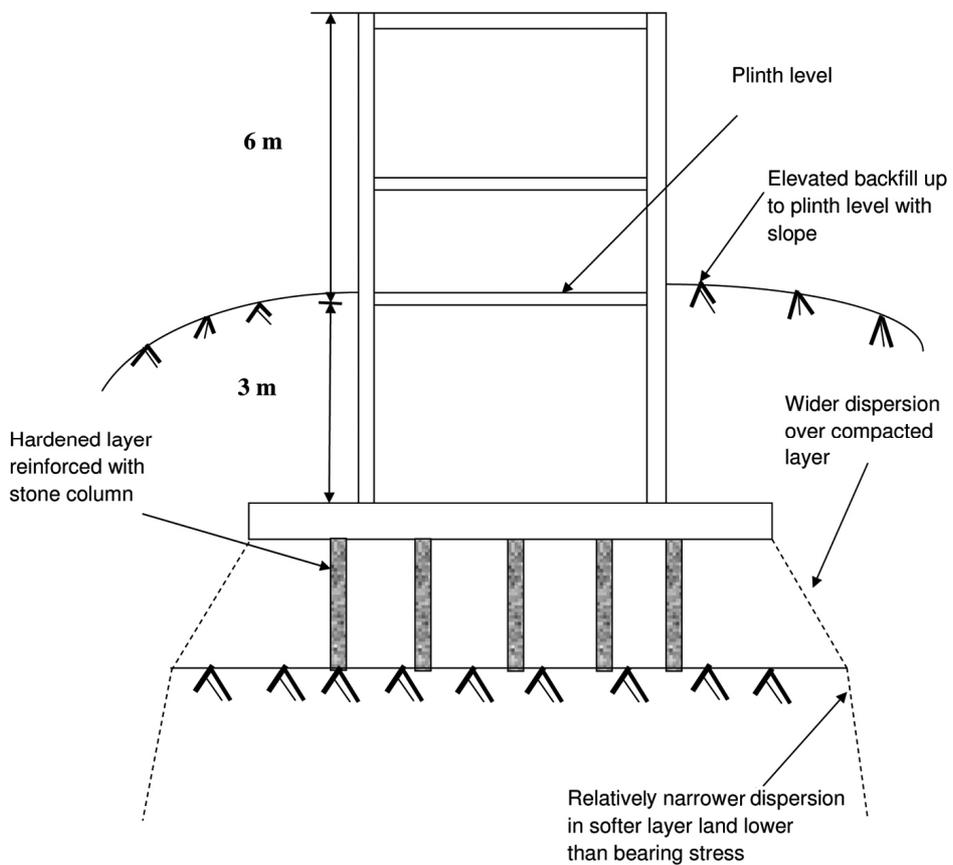
The failure of structure on an isolated footing in Eastern Kentucky gives an idea that isolated footing for such backfill soil leads to failure due to cracking through differential settlement<sup>13</sup>. This can probably be eliminated by including raft as a foundation for arresting differential settlement<sup>49,50</sup>. Though possibility of the overall structure getting tilted due to non-uniformity in the backfill does exist, it will not harm the structure as a whole. So, depending on the bearing capacity, a raft foundation may be made such that load is uniformly distributed over the hardened compacted layer and the problem of differential settlement can be arrested.

The inadequacy in the design of conveyance system for rainwater and proper drainage design in Kentucky has led to the accumulation of water near the area of construction and has led to subsidence<sup>22</sup>. To counteract these, an elevated ground may be chosen or created as in the form of flat construction ground with slightly sloping surface away from the flat plain, which can act as a pathway for drainage of water. The slightly sloping surface acts as a natural design for the drainage water, also reducing the possible infiltration from rain water or any other source. Figure 10 shows a detailed view of the construction where possible feasibility is suggested based on the behaviour of the fill. Figure 11 shows the overall proposed plan for construction on such a site.

In order to understand the implication of the above proposed scheme, gravity loading of a building consisting of two-storeys and four rooms in each storey has been calculated. The dimension of each room is taken to be 4 m × 4 m, the building is considered to be symmetric and to rest on a raft foundation. Loading is considered to be as prescribed in relevant Indian standard IS code IS 875-1987 (ref. 51). It has been found that intensity of loading under raft is 74 kN/m<sup>2</sup> at raft level. On the other hand, from the weight of the overburden under 3 m depth that the backfill soil has been withstanding, it is about 76.44 kN/m<sup>2</sup>. The result of a soil test for determining bearing capacity at backfill site of Jagganath coillery site, Talcher, Odisha, India showed a value of about 81.8 kN/m<sup>2</sup>, which also seems to support the proposed low-rise construction. However, for provision of an adequate safety factor, reinforcement of soil with stone column may help in ground improvement for raising construction on such backfill sites.



**Figure 8.** Broad experimental demonstration of reinforced demolished concrete waste as stone column.



**Figure 9.** Schematic representation of a typical cross-section of the soil-foundation-structure system on backfill soil.

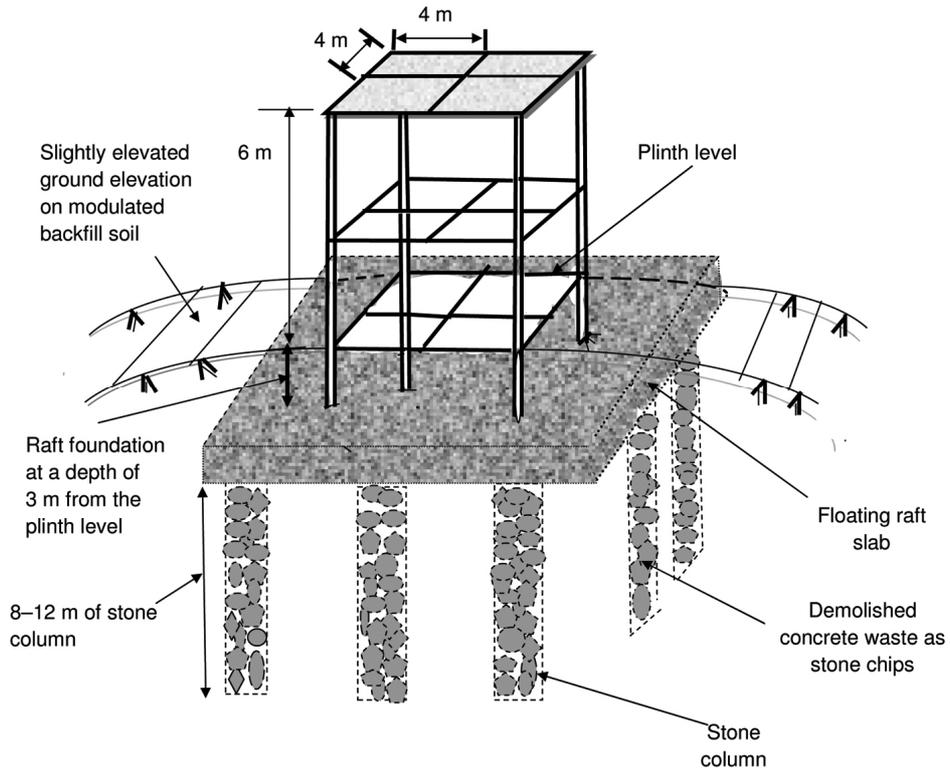


Figure 10. Detailed view of proposed two-storey building construction on backfill.

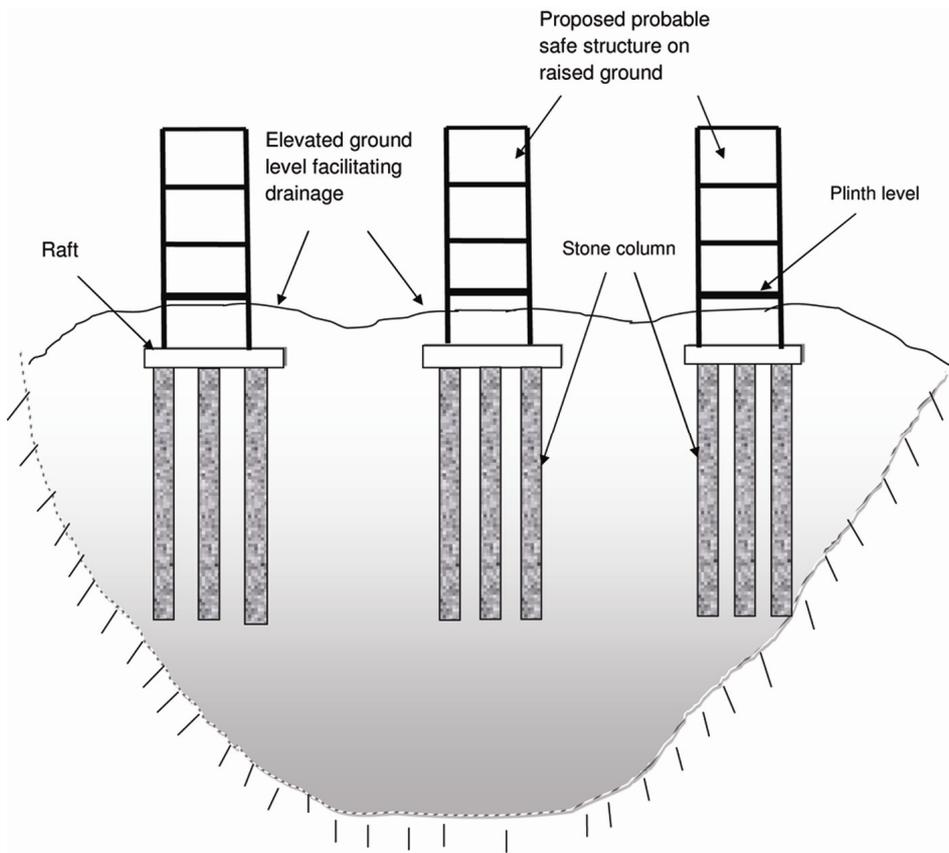


Figure 11. Proposed overview of the plan for construction on backfill.

## Concluding remarks

Increasing population puts great stress on our existing energy and resources. This further leads to an increase in mining activity and increase in the percentage of mine cover area. One of the major after-effects of mining is the generation of a large number of opencast, useless back-filled areas. Rehabilitation on such large opencast mine areas which have been backfilled with mine spoil is a real challenge from the point of view of achieving long-term sustainability for opencast mine activities. Here, the issues of heterogeneity and low bearing capacity of back-fill soil have been addressed by ground improvement using stone column. A special focus on a stone column with application of demolished concrete waste through broad experimental studies is been presented to avoid smearing effect as in case of regular aggregate. This technique of ground treatment protects the soil from failure due to collapse potential. Thus, the present study proposes a feasible scheme for constructing low-rise dwelling units. The detailed literature survey along with the list of references presented here will be useful for conducting further research in this direction.

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