Robotic Landscapes: Designing Formation Processes for Large Scale Autonomous Earth Moving

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Abstract. The technological advances in robotic construction equipment for large scale earth moving is revolutionizing how we think and act on terrain. With the development of HEAP, a full scale autonomous walking excavator by the Robotic Systems Lab of Professor Marco Hutter within the NCCR Digital Fabrication ETH Zurich [1], we will be able to shape large-scale natural granular material like sand, soil and gravel with unprecedented geometrical complexity according to a precise digital blueprint. The robotic platform enables feedback loops between the physical reality, the existing terrain and the proposed computational design, creating new potential for dynamic landscapes that can change over time. The ability to search, recognize and manipulate locally found materials allows us to rethink the design of the built environment to be economically and environmentally regenerative. In order to explore new applications and design methods for autonomous earth moving, a series of design studio has been implemented at the ETH Zurich as a collaboration between Professor Christophe Girot Chair of Landscape Architecture and Gramazio Kohler Research Chair of Architecture and Digital Fabrication. This article discusses the developed methods and techniques, as well as the experimental implementation within these studios. Rather than focusing on designing with explicit shapes or geometry, the students were encouraged to explore the making of form through a procedural understanding of robotic movements, computational design and granular material interaction.

Keywords: Digital Fabrication · Autonomous excavation · Large-scale landscape design · Robotic aggregation · Granular material

1 Introduction

Moving earth for large-scale landscapes and infrastructures becomes an increasingly important undertaking in relation to the sustainability of earth's ecosystems. Recent events like sea level rise, landslides, floods and drought indicate the delicate equilibrium that exists in natural systems. While hydraulic machines to construct large scale earthworks in response to these challenges has existed for over a millennium, taking

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informed and resilient action on any of these challenges has proven problematic [2]. The robotization of earth moving machinery enables the shaping of terrain using site specific, dynamic and open-ended construction processes capable to adapt over time [3]. This changes how landscapes or large-scale green infrastructures are formed and maintained [4]. Robotic earth moving questions the traditional linear understanding of landscape design, from conception to execution, as the appropriate way to respond to future challenges. Instead, site specific and local adaptations over time can have a dramatic impact on how the territory is configured. This paper will demonstrate robotic formation processes of natural granular materials like gravel and sand using computational design methods and robotic fabrication. The experiments were carried out in a sandbox during two consecutive landscape architecture design studios based on the capabilities of the autonomous walking excavator HEAP (Fig. 1).

Fig. 1. Students from the design studio exploring HEAP, the autonomous walking excavator that enables tactile and spatial feedback during digging cycles.

2 State of the Art

Robotic manipulation of natural granular material has been researched on various occasions, both as hardware in the development of construction equipment [5], and as computational experiments of robotic processes [6]. The difficulty with working with granular material is that it is virtually impossible to precisely simulate the outcome. This means that any manipulation method based on static geometry and predictable interaction requires the designer to understand the approximate behavior of the system that allows for gradual adaptation. Instead, robotic manipulation of granular material asks for continuous feedback loops between the robotic movement and the achieved form in an iterative manner. In this way, the construction process can adapt to unforeseen site conditions using parametric constraints [7]. Based on the ongoing research on HEAP at the NNCR Digital Fabrication at the ETH Zurich, perception, modeling, planning and control tools that are aware of the environment are being developed on an existing walking excavator platform. In contrast to existing platforms which are mostly based on position trajectories for the bucket motion, HEAP defines its trajectory by a force and torque. This means that it overcomes the limitations of current approaches that suffer from the widely diverse interaction forces in soil by adjusting its motion based the found material on site. An iterative digging approach then achieves the desired geometry by executing consecutive digging cycles.

While the technology for autonomous excavation are in a far stage of development, computational design strategies to leverage the architectural potential of the robotic manipulation of granular material is lacking behind. A first test of robotic granular material deposition was explored 2012 in an elective course at the ETH Zurich in a collaboration between professor Christophe Girot and professors Fabio Gramazio and Mathias Kohler. The processing of shapeless materials such as sand through digitally controlled machines equipped with sensors allowed the students to implement feedback-driven formation processes into their sand boxes. These formation processes were controlled using table mounted robotic arms. The main objective of these investigations was not the materialization of a predefined landscape condition, but rather the precise analysis and documentation of specific material properties and aggregation processes during the simulations. Other examples of the aggregation of granular material include robotic clay molding [8] or robotically positioning material in space from a distance and thereby creating differentiated architectural aggregations that are a direct expression of a dynamic and adaptive fabrication process by Gramazio Kohler Research [9]. These examples, however, do not address the specific potential that large-scale autonomous earth moving presents in the context of landscape architecture. The next section outlines the design research methods for the development of robotic formation processes in large-scale earth moving.

3 Methodology

The research outlined in this paper is situated in the larger research goal on construction robotics of the NCCR Digital Fabrication at the ETH Zurich. The development of the robotic platform by HEAP is driven by state of the art technological developments in robotic planning and control systems. The research described in this paper responds to these technological advancements by investigating its specific architectural potential and possible application areas in large-scale earth moving. The work is conducted in three interconnected phases. The first phase encompassed the improvement of computational tools that can model loose and granular material efficiently and procedurally. Based on digital elevation data, a powerful digital landform editing tool using 2D distance functions named Docofossor has been developed [10]. To better understand robotic formation processes for large-scale earth moving equipment, the second phase initiated a landscape architectural design research studio to study the architectural potential of robotic terrain modeling. The first and second iteration of this design studio have been completed successfully in fall 2017 and in fall 2018 respectively, and the results are discussed in this paper. The third phase will continue in summer 2019 transferring the results and findings onto the full-scale robotic platform HEAP.

3.1 Computational Design System

For every studio, a custom robotic system designed and build to address specific granular material interactions in a sand box without having to resort to generalizations in granular material interaction. The first design research studio explored direct manipulation in the sand box, while the second used material deposition. By limiting the terrain modeling operation per studio to merely shifting or deposition only, this setup allowed to study a specific operation in depth. The robotic process consists of a loop between the geometric description of the design (1), the sensing (2) and the manipulation (3) of the material (see Fig. 2). To manipulate the material, the system builds upon a collaborative robotic arm (Universal Robot UR10), onto which a custom end effector is mounted. The sandbox in which the manipulation takes places becomes the abstract approximation of full scale robotic terrain modeling. While the physics in the scaled sand box are not the same as they would be in full scale excavation, it establishes a close relation to the formation principles of the robotic platform HEAP. The scale less nature of the box makes it an ideal sketching tool to experiment with granular material and robotic modeling. The design description contains procedural rules in the visual programming language Rhino Grasshopper. Perception was implemented with a 6-axis force torque sensor (Robotiq ft150) and a 3D scanner (Kinect V2) (e.g. tactile, spatial), while the manipulation was done by direct contact or deposition of material (e.g. excavate, shift, compress, deposit). It made it possible to sense the material in real time and adjust the amount of compression or deposition. The feedback loop between the individual manipulations, the sensing of the material and the design rules initiated a new landscape design method, enabling dynamic and open-ended construction approaches.

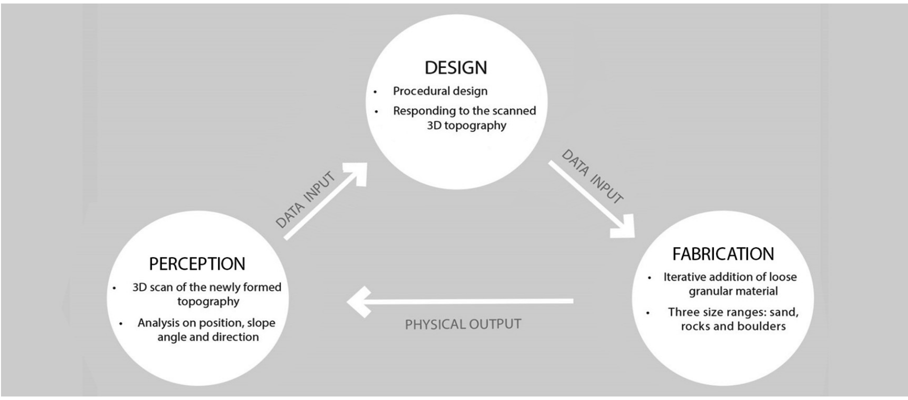

Fig. 2. Diagram of the robotic design process encompassing the feedback loop between perception (sense), modeling (design) and fabrication (manipulate).

3.2 Granular Material

Each studio resourced granular material of different texture and material composition. Soil is almost never homogeneous, and differs vastly in how it can be applied [11]. Because of this, robotic modeling of granular material needs to be able to adapt to continuously changing conditions. It is challenging to sense or simulate the exact soil composition. Furthermore, the volume of compacted vs loose soil is difficult to estimate. This specific condition is the reason why robotic landscape fabrication is such a challenge today. To be able to adapt in real time to changing site conditions, a design will have to be encoded in topological rules that can transform its form over time.

4 Experiments

4.1 Robotic Landscapes I

The first design studio in fall 2018 studied in-place manipulation of granular material. The site of the studio was located on the Ticino River in Switzerland where sediments deposited over thousands of years created the Valle Riviera. The A2 highway running along the river is the main connector but at the same time main border and noise emitter in the valley. Using only local material, the task was to design a new linear landscape park and sound barrier along the highway and redefine the relation to the dynamic river. By applying acoustic rules of ground-, screening- and reflection effects, various geometric compositions for the earthwork were explored as a functional sound barrier, a new highway scenography and a landscape park.

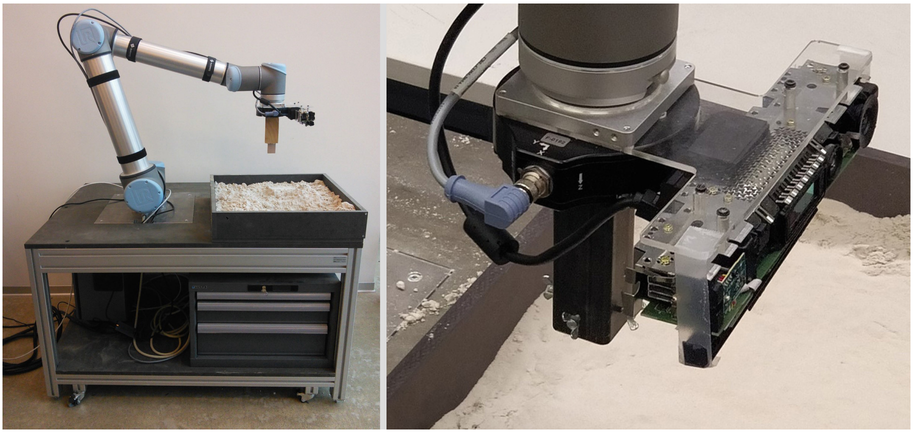

Fig. 3. Robotic design system and end effector using a robotic arm, 3D scanner, force sensor, tool holder and a sandbox.

Robotic Setup I. The complete robotic setup encompassed a robotic arm, an end effector and a sandbox. The end effector consisted of a force sensor and a 3D scanner for perception, combined with a tool holder to interact with the sand (Fig. 3). For this first studio, we choose a homogeneous modeling sand to limit the parameters for the students. The maximum allowable slope angles depend heavily on the used modeling sand, which were determined by experimentation in the sand box. In turn, the forces exerted on the robotic arm during operation were translated to estimate change in volume. By iteratively shifting and compressing the sand, a final topography was created. No sand could ever leave or enter the box, which meant that all operations had to be carried out by either shifting and/or compressing the material. This resulted in a wide variety of formal expressions in the earthworks while maintaining topological and acoustic performance.

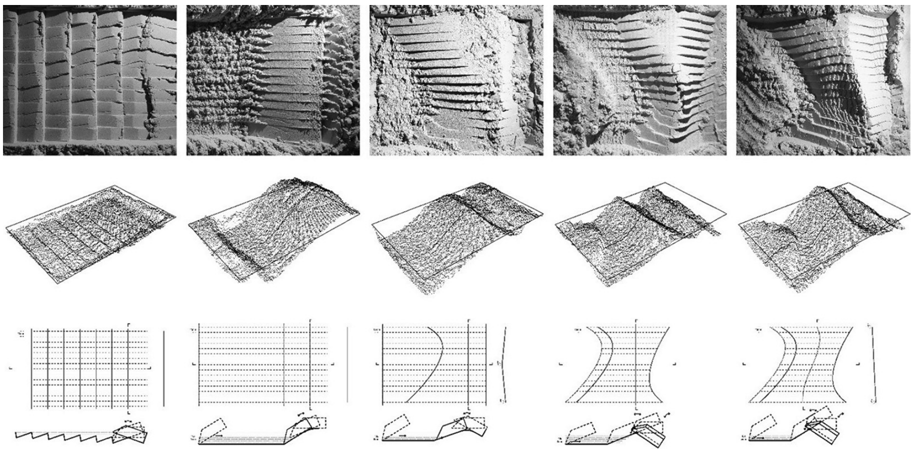

Fig. 4. Feedback driven design explorations by students Ladina Ramming and Thorben Westerhuys showing the movement of the tool in the sand (bottom row), the 3D scan (middle row) and the formal expression (top row).

Locally Informed Transformation. Two main approaches were explored in the studio by either shifting and/or compressing material. The first operation was to shift material locally, informed by approaching and touching the sand with the tool until it would exert a certain force to the end-effector. From there, sideways movements shifted the material locally where a second operation would finish the surface (Fig. 4). The direction of the material shift came from the computational design that was informed by existing slope angles and orientation from the scan of the sand box. The amount of shifted material was also controlled by the 3D scanner, for instance when it would reach a desired height or volume.

Geometry by Iteration. The second operation explored iterative compression of the sand. Students were asked to design their own tool, which in turn resulted in a wide range of geometries. However, often simple tools that would perform complex iterative motions resulted in the most unexpected outcomes (Fig. 5). The iteration of the tool inside the sand box enabled the creation of a general overall form for screening effects, while local geometric complexity was used to diffuse the sound coming from the highway.

Fig. 5. Sandbox experiment by students Ladina Ramming and Thorben Westerhuys showing the linear barrier and its intricate geometries made by iterative robotic movements of the end effector.

4.2 Robotic Landscapes II

The second iteration of the design studio in fall 2019 studied multi-granular deposition. Since 2011, a chain of major tectonic events has deeply affected the village of Bondo in the Canton of Grisons, Switzerland where the partial geological collapse in 2017 of the Piz Cengalo Mountain is requiring urgent remedial measures. Heavy rainfall will undoubtedly result in further landslides worsening the precarious situation in the coming years. In response to the challenges posed by the disaster, the studio asked students to develop new topographic solutions only using sand, gravel and rock from the landslide. By designing robotic principles and procedural design solutions, a new dynamic infrastructure was formed over time that mediated future hazards in this unstable alpine landscape.

Robotic Setup II. Three different grain sizes were used to simulate the creation of large boulders, gravel and sand found on site. A new end effector was developed to enable the release of three different grain sizes from the robotic arm (Fig. 6). The material was led through the funnel where it was transported with a small conveyor belt to precisely control the amount of material leaving the end-effector. The grain sizes conceptually translated to fixed and static geometry in the form of large boulders to a more fluid geometry out of sand that is under constant influence of erosion and sedimentation. A 3D scanner enabled an iterative design approach through spatial perception. The computational design tool Docofossor allowed to implement results from the sandbox into a large scale digital topography. Subsequently, the designs were tested in the mass movement simulation software RAMMS to analyze how the topographic designs would modify the path and speed of the debris flows [12].

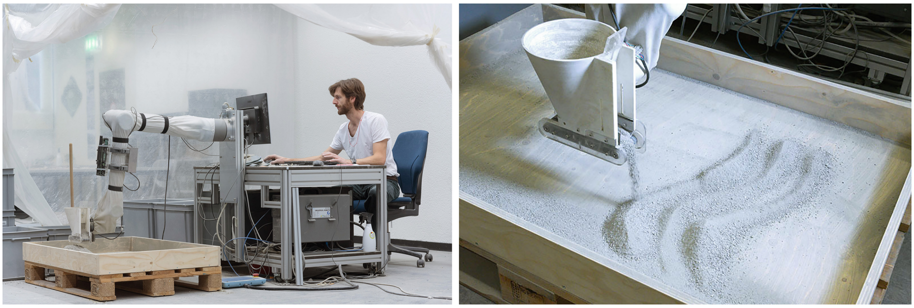

Fig. 6. Student Basil Schück working on the robotic setup and end-effector that deposits granular material with an active funnel.

Material Interaction. The material available to the students consisted of actual material from the debris flow of 2017. It was sourced on site and filtered to three different grain sizes. The students were asked to deposit the material in a logical way that would strengthen the protection against future debris flows and to maximize natural transportation through the site. It became clear that larger rocks were harder to control then fine sand particles, influencing the roughness of the surface which in turn controlled the speed and force of the debris flows. The sand box was then buildup of various layers with different grain sizes, informing the terrain with maximum slope stability and protection against erosion.

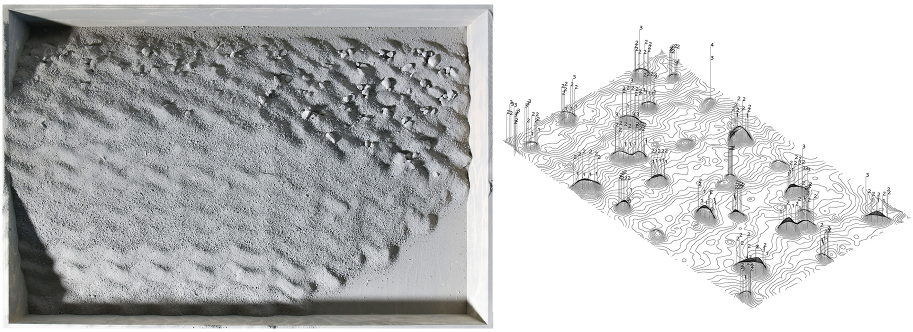

Fig. 7. Sandbox experiment showing the buildup granular material by students and the automated recognition of larger rocks in the sandbox by students Kelly Meng and Dawit Tadesse (right).

Responding to Existing Terrain. Various approaches to the computational design system were explored. The recognition of a sand box modeled after real world conditions was done with the 3D scanner. Apart from slope and orientation of the sand, rock recognition was applied (Fig. 7). After a debris flow event, rocks of up to 20 tons will be spread over the landscape, and subsequently hard to re-locate. A random distribution of rocks in the sandbox generated a design language from this found material, where the performative aspects like water runoff and debris flow re-direction continue to function while leaving those large boulders in place. This project generated a new design every time the rocks were distributed differently in the sand box.

Dynamic Aggregation. Another method used the 3D scanner to measure the geometry after every iteration of material deposition. The final geometry was defined by its height along the deposition paths. Once new material was deposited in the sand box, the resulting geometry was scanned and analyzed towards the final design. In responds, the place and amount of material found in the box informed the subsequent robotic movements. This method was implemented in a randomly filled sand box as a way to mimic actual on site conditions (Fig. 8).

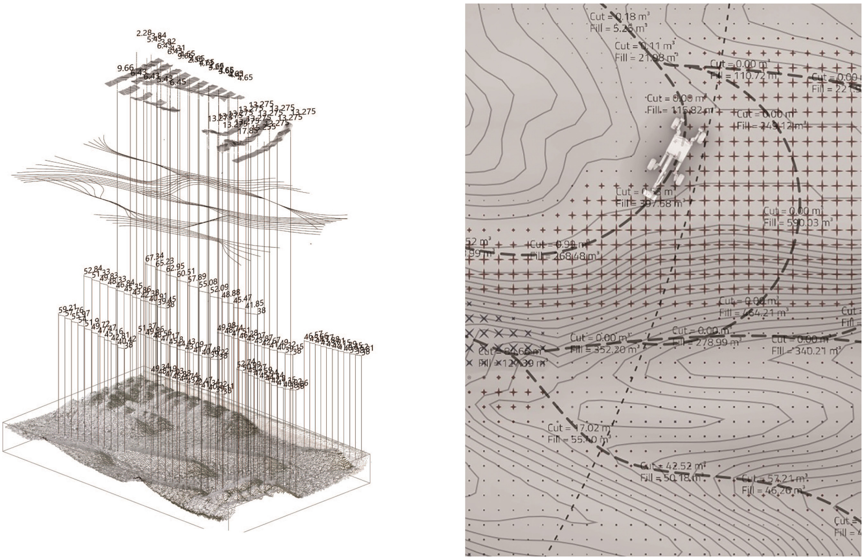

Fig. 8. The robotic process showing the scanned material and design parameters (left) and the design strategy by students Lip Jiang Lee, Matthew Lee and Yorika Sunada.

Open Ended Formation. Finally, the last main topic explored was the transformation of the topography as an open-ended formation process. Because debris flows and the erosion and sedimentation processes that happen within are very hard to simulate, this part was done conceptually as a large scale landscape design. The designs did not only consist of one final end-state, but were modeled after three consecutive debris flows spanning roughly 10 years (Fig. 9). The first event would bring 400’000 m^3 of material (t1), the second 150’000 m^3 (t2) and the third 50’000 m^3 (t3). This meant that each of the three designs had to allocate space for the deposition of the debris flows while transporting the material locally balancing cut and fill operations. There are many parameters that determine the landscape design at any moment in time. Clearly visible in Fig. 10 is the build-up of the original terrain (shown in white) and the subsequent material depositions (dashed lines for t1, t2 and t3). The overall topology was informed by the simulations to direct the debris flows away from the village. At a smaller scale, topological rules control maximum slope angles, volume, and the distribution of sand, rocks and boulders. The main body of the terrain is constructed with sand, but wherever the simulation showed high sheer stress on the channel embankments boulders are put in place to maintain the resilience of the topological system. Finally, rich soil placed on higher levels contribute to vegetation growth that in turn stabilize the ground. To summarize: the design combines dynamic aggregation and open-ended formation to form a continues construction cycle. It demonstrates how terrain can be formed by natural processes (of erosion and sedimentation) and robotic processes working together over time.

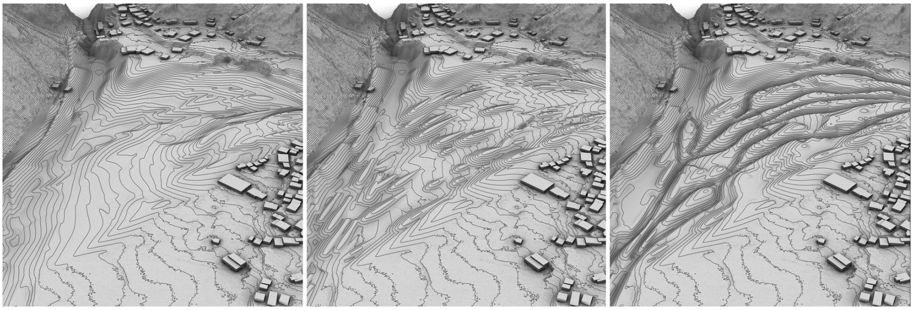

Fig. 9. Modeling of the topographic change over time using the computational terrain modeling tool Docofossor by students Lip Jiang Lee, Matthew Lee and Yorika Sunada.

5 Results

The results of the Robotic Landscape I design research studio show how feedback loops enables adaptive and site specific topographic designs. Through the use of the force sensor and the 3D scanner, the topography is formed only when the end-effector operates in the sand box. This means that the code by itself does not describe a form, rather, the form comes into being in the process of digital-physical interaction. The final form will only be revealed once the actual construction is finished. In turn, the results of the Robotic Landscapes II design research show how future landscape topologies can be designed and constructed. Instead of predefined and static modifications of the landscape, robotic systems enable the shaping of terrain using site-specific, dynamic, and open-ended construction processes. By manipulating natural granular material, these processes can then model terrain that evolves over time. Figure 11 shows the many outcomes that the 2nd studio produced. They vary in topology based on how the volume calculations, slope analysis, rock recognition and multi-material deposition is interpreted by the computational design system. By integrating the feedback loop in earth moving operations, form and process are equally considered in the investigation of spatial relationships that exist in surface structures traversing urban, infrastructural and natural landscapes. It clearly showed that by designing new topological rules for forming terrain, a new-found equilibrium can be devised between the natural and the manufactured.

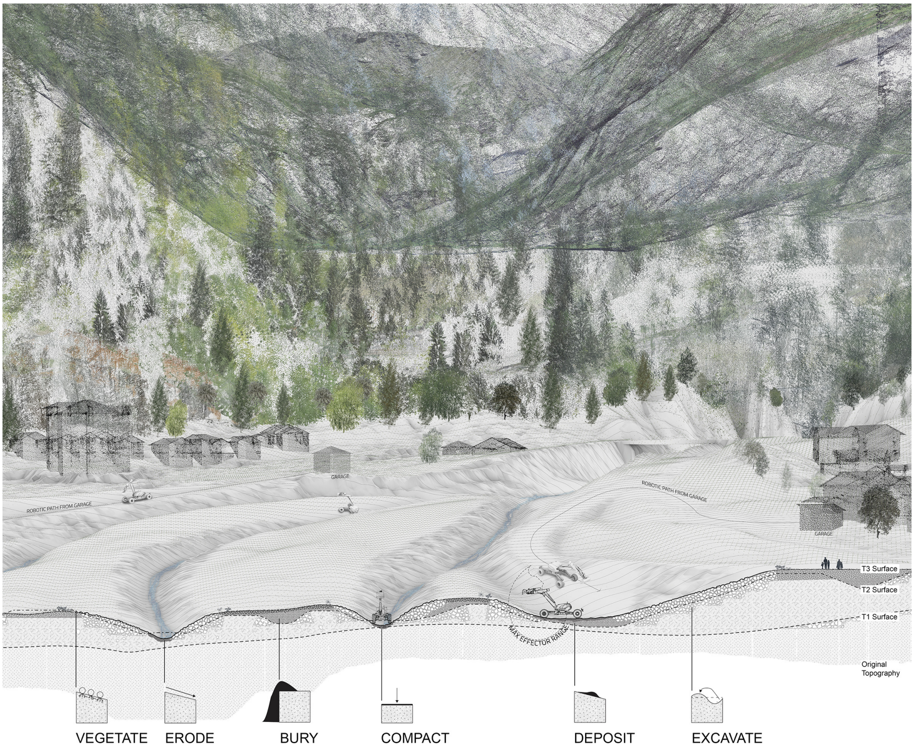

Fig. 10. Visualization of the adapted landscape by the autonomous robotic excavator after 10 years of debris flows and iterative robotic construction by students Lip Jiang Lee, Matthew Lee and Yorika Sunada.

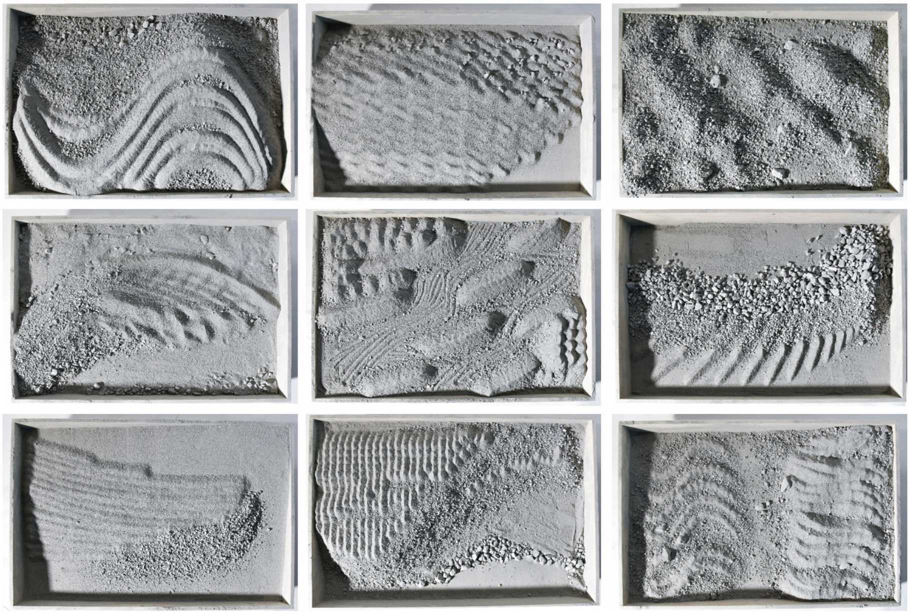

Fig. 11. Various sand box experiments as a result of dynamic modeling processes using multi granular material. They range from terrain informed transformations, geometry by iteration, dynamic aggregation and open-ended formation strategies as remedial measures against debris flow hazards.

6 Conclusion

The manipulation of terrain with robotic processes enables us to react and steer natural forces for a sustainable and resilient landscape future. The design explorations on the formation of found granular material showed the importance of a feedback loop between the computational tool and the robotic system. This allows the fabrication of complex and informed geometries using robotic processes acting directly on the physical environment. It may shift the status quo in environmental engineering from specific and static solutions to an ever changing infrastructure that can respond dynamically to changing site conditions and evolving civic needs. The first experiment showed how iterative fabrication using feedback loops can foster an adaptive design approach dependent on local site conditions. The second experiment build upon this method by demonstrating the robotic agency as a permanent force in the landscape, allowing for continuous, open ended transformation over time. A third installment of the design studio starting in fall 2019 will combine excavation, deposition and continuous observation in one robotic design system. This will level the technological implementation of the experiments to the level of the robotic engineering in preparation of a 1:1 demonstration with the autonomous robotic excavator later that year.

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