Designation: E2828/E2828M − 20

Standard Test Method for Evaluating Response Robot Mobility Using Symmetric Stepfields Terrains[1]

This standard is issued under the fixed designation E2828/E2828M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

The robotics community needs ways to measure whether a particular robot is capable of performing specific missions in complex, unstructured, and often hazardous environments. These missions require various combinations of elemental robot capabilities. Each capability can be represented as a test method with an associated apparatus to provide tangible challenges for various mission requirements and performance metrics to communicate results. These test methods can then be combined and sequenced to evaluate essential robot capabilities and remote operator proficiencies necessary to successfully perform intended missions.

The ASTM International Standards Committee on Homeland Security Applications (E54) specifies these standard test methods to facilitate comparisons across different testing locations and dates for diverse robot sizes and configurations. These standards support robot researchers, manufacturers, and user organizations in different ways. Researchers use the standards to understand mission requirements, encourage innovation, and demonstrate break-through capabilities. Manufacturers use the standards to evaluate design decisions, integrate emerging technologies, and harden systems. Emergency responders and soldiers use them to guide purchasing decisions, align deployment expectations, and focus training with standard measures of operator proficiency. Associated usage guides describe how these standards can be applied to support various objectives.

Several suites of standards address these elemental capabilities including maneuvering, mobility, dexterity, sensing, energy, communications, durability, proficiency, autonomy, and logistics. This standard is part of the Mobility Suite of test methods.

1. Scope

1.1 This test method is intended for remotely operated ground robots operating in complex, unstructured, and often hazardous environments. It specifies the apparatuses, procedures, and performance metrics necessary to measure the capability of a robot to traverse complex terrains in the form of symmetric stepfields. This test method is one of several related mobility tests that can be used to evaluate overall system capabilities.

1.2 The robotic system includes a remote operator in control of all functionality, so an onboard camera and remote operator display are typically required. Assistive features or autonomous behaviors that improve the effectiveness or efficiency of the overall system are encouraged.

1.3 Different user communities can set their own thresholds of acceptable performance within this test method for various mission requirements.

1.4 *Performing Location*—This test method may be performed anywhere the specified apparatuses and environmental conditions can be implemented.

1.5 *Units*—The International System of Units (SI Units) and U.S. Customary Units (Imperial Units) are used throughout this document. They are not mathematical conversions. Rather, they are approximate equivalents in each system of units to enable use of readily available materials in different countries. This avoids excessive purchasing and fabrication costs. The differences between the stated dimensions in each system of units are insignificant for the purposes of comparing test method results, so each system of units is separately considered standard within this test method.

[1] This test method is under the jurisdiction of ASTM Committee E54 on Homeland Security Applications and is the direct responsibility of Subcommittee E54.09 on Response Robots.

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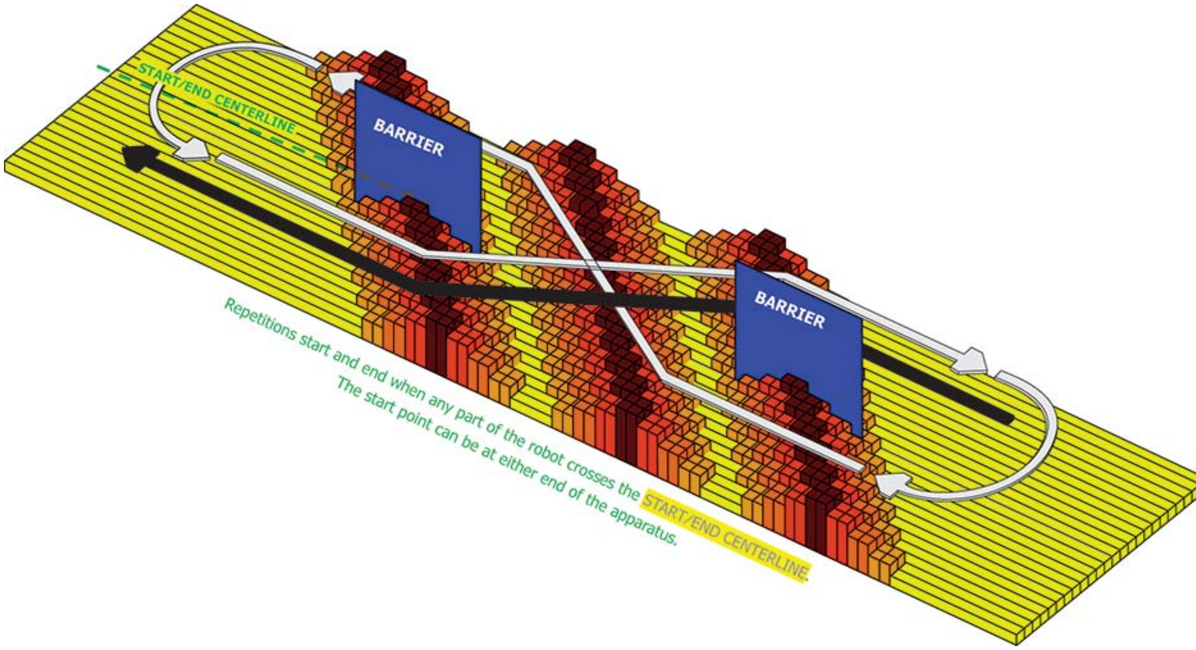


FIG. 1 Overview of the Symmetric Stepfield Terrain Apparatus

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2521 Terminology for Evaluating Response Robot Capabilities

2.2 *Other Standards:*

National Response Framework U.S. Department of Homeland Security[3]

NIST Special Publication 1011-I-2.0 Autonomy Levels for Unmanned Systems (ALFUS) Framework, Volume I: Terminology, Version 2.04[4]

3. Terminology

3.1 *Definitions*—The following terms are used in this test method and are defined in Terminology E2521: *abstain*, *administrator* or *test administrator*, *emergency response robot* or *response robot*, *fault condition*, *operator*, *operator station*, *remote control*, *repetition*, *robot*, *teleoperation*, *test event* or *event*, *test form*, *test sponsor*, *test suite*, *testing target* or *target*, *testing task* or *task*, and *trial* or *test trial*.

3.2 The following terms are used in this test method and are defined in ALFUS Framework Volume I:3: *autonomous*, *autonomy*, *level of autonomy*, *operator control unit (OCU)*, and *semi-autonomous*.

4. Summary of Test Method

4.1 This test method is performed by a remote operator controlling the robot out of sight and sound of robot within the test apparatus. The robot follows one of two defined paths in the specified terrain requiring the robot to overcome challenges including pitch, roll, traction, and turning on uneven surfaces within open or confined spaces.

4.2 *The Figure-8 Path (forward)* is a continuous forward path through the terrain with alternating left and right turns to avoid barriers. It can be used to demonstrate terrain traversal over long distances within a relatively small apparatus. The continuous traverse is shown as the white path (see Fig. 1 and Fig. 2).

4.3 *The Zig-Zag Path (forward/reverse)* is an end-to-end path that requires forward and reverse traversal through the terrain with alternating left and right turns to avoid barriers. This can be used to demonstrate traversal of the terrain within confined spaces. The down-range traverse, shown as the white path, is performed in a forward orientation and the up-range traverse, shown as the black path, is performed in reverse (see Fig. 1 and Fig. 3).

4.4 The robot starts on one side or the other of a lane full of fabricated symmetric stepfield terrain at a chosen scale. The robot follows either the figure-8 path (forward) or the zig-zag

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Federal Emergency Management Agency (FEMA), P.O. Box 10055, Hyattsville, MD 20782-8055, http://www.fema.gov.

[4] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov.

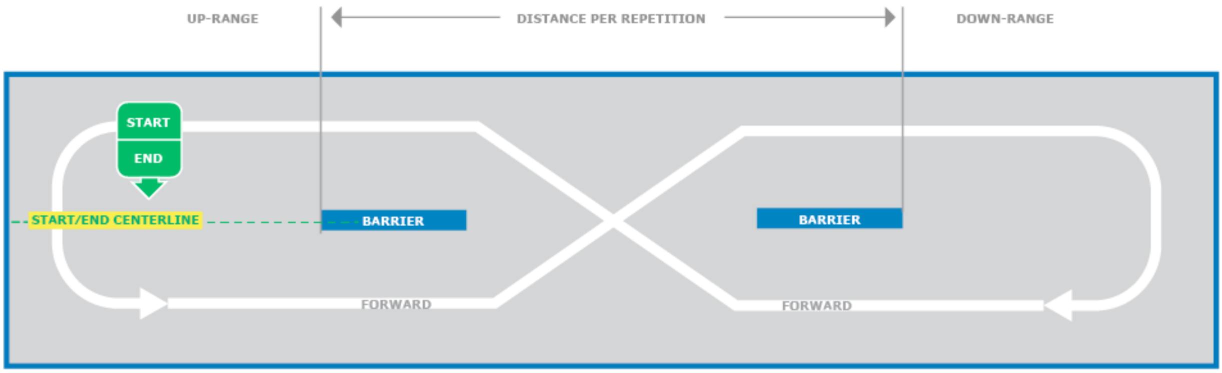
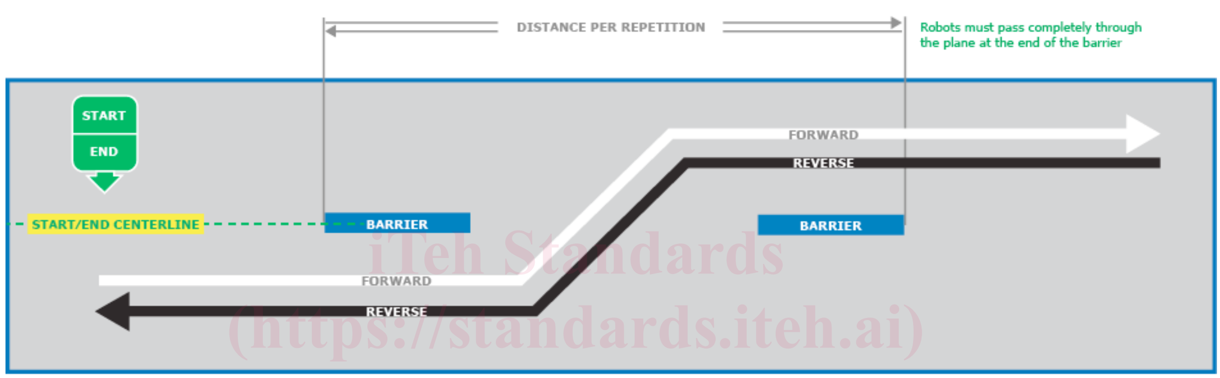


Figure-8 repetitions start and end when any part of the robot crosses the START/END CENTERLINE and approximately follows the white path. Returning to the start position completes one repetition. The distance traversed is measured from the outer edges of both barriers. (Note: The start point can be at either end of the apparatus.)

FIG. 2 Top View Showing the Figure-8 Path (Forward) Defined by the Barriers



Zig-Zag repetitions start and end when any part of the robot crosses the START/END CENTERLINE and approximately follows the white and black paths. Each repetition completes alternating forward and reverse turns past the ends of the barriers. The distance traversed is measured from one end of the apparatus to the other. The traversal length of the robot beyond the barriers is disregarded because of various size robots. (Note: The start point can be at either end of the apparatus.)

FIG. 3 Top View Showing the Zig-Zag Path (Forward/Reverse) Defined by the Barriers

path (forward/reverse) between the two barriers. The figure-8 path (forward) repetition is completed when the robot crosses the start/end centerline of the lane without a fault after approximately following the white path. The zig-zag path (forward/reverse) repetition is completed when the robot crosses the start/end centerline without a fault after approximately following the white and black paths.

4.5 *Potential Faults Include:*

4.5.1 Any contact by the robot with the apparatus that requires adjustment or repair to return the apparatus to the initial condition;

4.5.2 Any visual, audible, or physical interaction that assists either the robot or the remote operator;

4.5.3 Leaving the apparatus during the trial.

4.6 Test trials shall produce enough successful repetitions to demonstrate the reliability of the system capability or the remote operator proficiency. A complete trial of 10 to 30 repetitions in either one of the defined paths should take 10 to 30 min to complete. When measuring system capabilities, it is important to allow enough time to capture a complete trial with an expert operator. When measuring operator proficiency, it is important to limit the time of the trial so that novice and expert operators are similarly fatigued.

4.7 There are three metrics to consider when calculating the results of a test trial. They should be considered in the following order of importance: completeness score, reliability, and efficiency. The results from the figure-8 path (forward) and the zig-zag path (forward/reverse) are not comparable because they measure different capabilities. The results from different scales of test apparatus are also not comparable because they represent different clearances and distances.

5. Significance and Use

5.1 This test method is part of an overall suite of related test methods that provide repeatable measures of robotic system mobility and remote operator proficiency. This symmetric stepfield terrain specifically challenges robotic system locomotion, suspension systems to maintain traction, rollover tendencies, self-righting in complex terrain (if necessary), chassis shape variability (if available), and remote situational

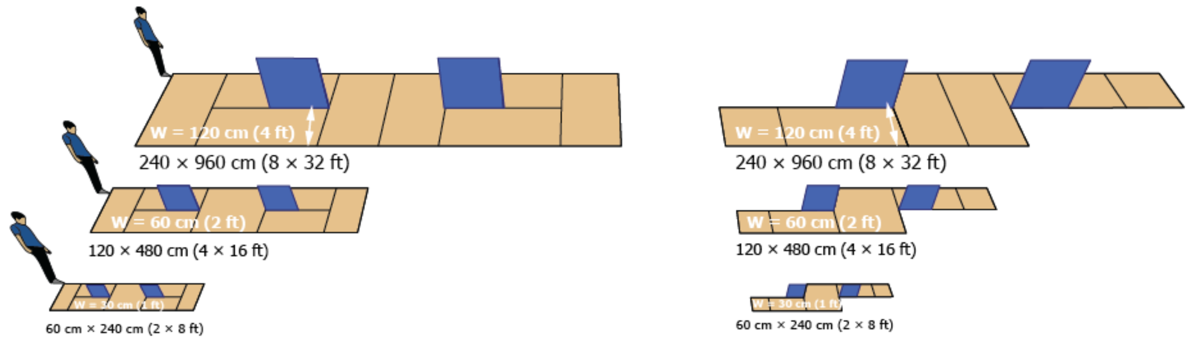


FIG. 4 Both Paths are Scalable to Represent Different Environments

awareness by the operator. As such, it can be used to represent modest outdoor terrain complexity or indoor debris within confined areas.

5.2 The overall size of the terrain apparatus can vary to provide different constraints depending on the typical obstacle spacing of the intended deployment environment. For example, the terrain with containment walls can be sized to represent repeatable complexity within bus, train, or plane aisles; dwellings with hallways and doorways; relatively open parking lots with spaces between cars; or unobstructed terrains.

5.3 The test apparatuses are low cost and easy to fabricate so they can be widely replicated. The procedure is also simple to conduct. This eases comparisons across various testing locations and dates to determine best-in-class systems and operators.

5.4 *Evaluation*—This test method can be used in a controlled environment to measure baseline capabilities. It can also be embedded into operational training scenarios to measure degradation due to uncontrolled variables in lighting, weather, radio communications, GPS accuracy, etc.

5.5 *Procurement*—This test method can be used to identify inherent capability trade-offs in systems, make informed purchasing decisions, and verify performance during acceptance testing. This aligns requirement specifications and user expectations with existing capability limits.

5.6 *Training*—This test method can be used to focus operator training as a repeatable practice task or as an embedded task within training scenarios. The resulting measures of remote operator proficiency enable tracking of perishable skills over time, along with comparisons of performance across squads, regions, or national averages.

5.7 *Innovation*—This test method can be used to inspire technical innovation, demonstrate break-through capabilities, and measure the reliability of systems performing specific tasks within an overall mission sequence. Combining or sequencing multiple test methods can guide manufacturers toward implementing the combinations of capabilities necessary to perform essential mission tasks.

6. Apparatus

6.1 The equipment required to perform this test method includes a symmetric stepfield terrain, barriers to define the robot path, a containment structure, and a timer. The main apparatus dimension to consider is the minimum clearance width (W) for the robot throughout the specified path (see Fig. 4). The minimum clear width should be chosen to represent typical obstacle spacings of the intended deployment environment. The minimum clearance width is typically set to 30 cm [1 ft], 60 cm [2 ft], 120 cm [4 ft], or 240 cm [8 ft] to efficiently use available construction materials, although other apparatus sizes can be used. All apparatus dimensions scale proportionally with the minimum clearance width (see Fig. 5). For example, the overall width of the terrain lane is 2W, and the overall length of the terrain lane is at least 6W. It can be longer for larger robots needing more space to maneuver around the barriers while staying on the terrain. When choosing a specific minimum clearance width for the apparatus, note the resulting data is not comparable to other apparatuses with different minimum clearance widths.

6.2 *Stepfield Terrain*—The symmetric stepfield terrain forms diagonal hills and valleys. The terrain is discretized into step tops with square dimensions of $\frac{1}{6}$ A and elevation changes of $\frac{1}{12}$ A. This makes symmetric stepfield terrains easy to fabricate with typical square lumber posts (see Fig. 6). Apparatuses with A = 120 cm [48 in.] can be made with clusters of four 10 cm [4 in.] square posts cut to appropriate lengths to make each step. Apparatuses with A = 60 cm [24 in.] can be made with single 10 cm [4 in.] square post cut to appropriate lengths to make each step. Apparatuses with A = 30 cm [12 in.] can be made with single 5 cm [2 in.] square post cut to appropriate lengths to make each step (see Fig. 7). The fabricated elements of the symmetric stepfield terrain are an array of square lumber posts cut to various unit lengths depending on the minimum clearance width of the overall apparatus. The posts stand upright on end to form diagonal hill features that are 5 units tall at their peaks.

6.3 *Barriers to Define the Robot Path*—The barriers placed within the terrain must provide visual guidance for the remote robot operator to correctly traverse the defined figure-8 path (forward) or zig-zag path (forward/reverse). The barrier can be made from any solid or porous material that provides visual guidance. They should be sturdy and easily repaired or replaced after contact with the robot. The barrier's overall thickness shall remain less than 5 % of the minimum clearance width and the length shall equal W.

6.4 *Containment Structure*—The symmetric stepfield terrain posts need to be contained so they do not move relative to one

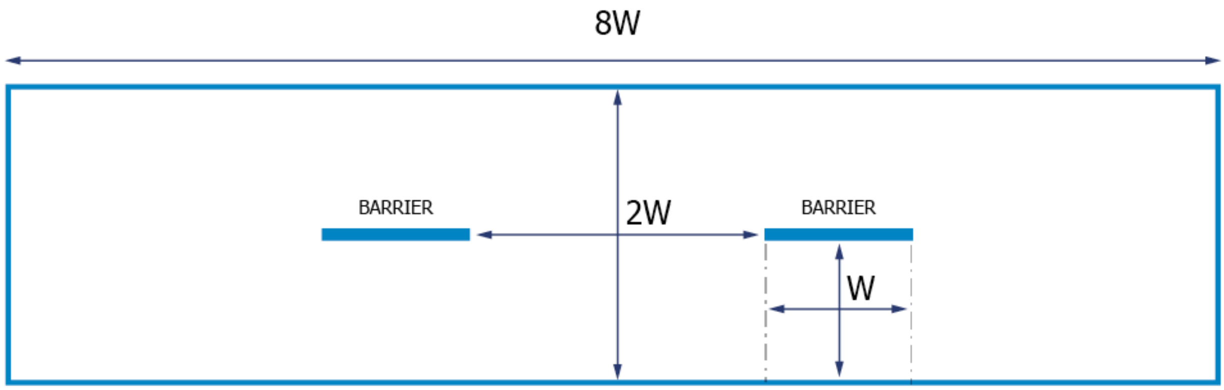


FIG. 5 Top View of a Test Apparatus Showing Dimensions Scale Proportionally to the Minimum Clearance Width (W)

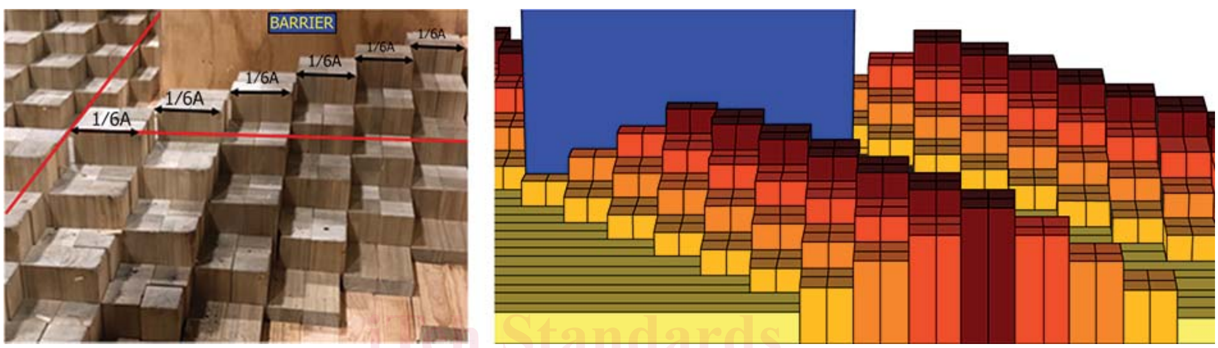


FIG. 6 Details of a Symmetric Stepfield

another (see Fig. 9). The minimum containment is an underlayment with a lumber border about half the height of the tallest posts. Walls can be fabricated to contain the robot as well as the terrain. This provides an extra level of difficulty for the robot. It can also provide a safety barrier for nearby personnel within a test facility. The fabricated wood walls are typically supported with arches over top. Shipping containers can also enclose test methods and turn a parking lot into a test facility. Apparatuses with minimum clearance width W = 120 cm [4 ft] can be slightly undersized to fit into a standard shipping container which has an interior width less than 2400 cm [8 ft]. The container walls should be lined with wood panels to cover the corrugated steel and have enough thickness to fill any gaps between the wall and the terrain.

6.5 *Other Devices*—A timer is used to measure the elapsed time of the trial. It provides a deterministic indication of trial start and end times to minimize uncertainty. It can count-up or count-down but should have a settable duration in minutes. A stopwatch can also be used. A light meter is necessary if testing in lighted and dark environments. A lighted environment is considered >150 lx and dark environment is considered <0.1 lx.

7. Hazards

7.1 Functional emergency stop systems are essential for safe remote or autonomous robot operation. The emergency stop on the operator control unit shall be clearly marked and accessible. The emergency stop on the robot chassis, if available, should also be marked. All personnel involved in testing shall familiarize themselves with the locations of all emergency stops prior to conducting trials.

7.2 Emergency stop systems shall be engaged prior to approaching a remotely operated robot. Constant communication is essential between the robot and the operator until the robot is safely within the test apparatus and people are either outside the apparatus or at a safe distance. The remote operator may not be aware that someone is interacting with the robot when they start to drive, actuate a manipulator, or move the robot in some other way. Avoid standing directly in front of the robot, behind the robot, or within reach of the manipulator arm unless the robot is completely deactivated.

7.3 Safety equipment such as a belay shall be used from a safe distance to prevent robot damage if necessary. Intervention by hand to try to stop a robot from falling or flipping over is to be prohibited. The belay shall be required for this. Any interaction with the robot, including tightening the belay to save the robot, is considered a fault for scoring purposes.

7.4 Test apparatuses that are intended to challenge robot mobility can be complex and unstable for humans. Proper footwear and other personal protective equipment shall be worn to mitigate risk. Caution is required when attending to a robot or carrying equipment within the apparatus.

8. Procedure

8.1 *Identify the Robot Configuration*—The robotic system configuration being tested shall be identified and uniquely named (for example, make, model, configuration), including all

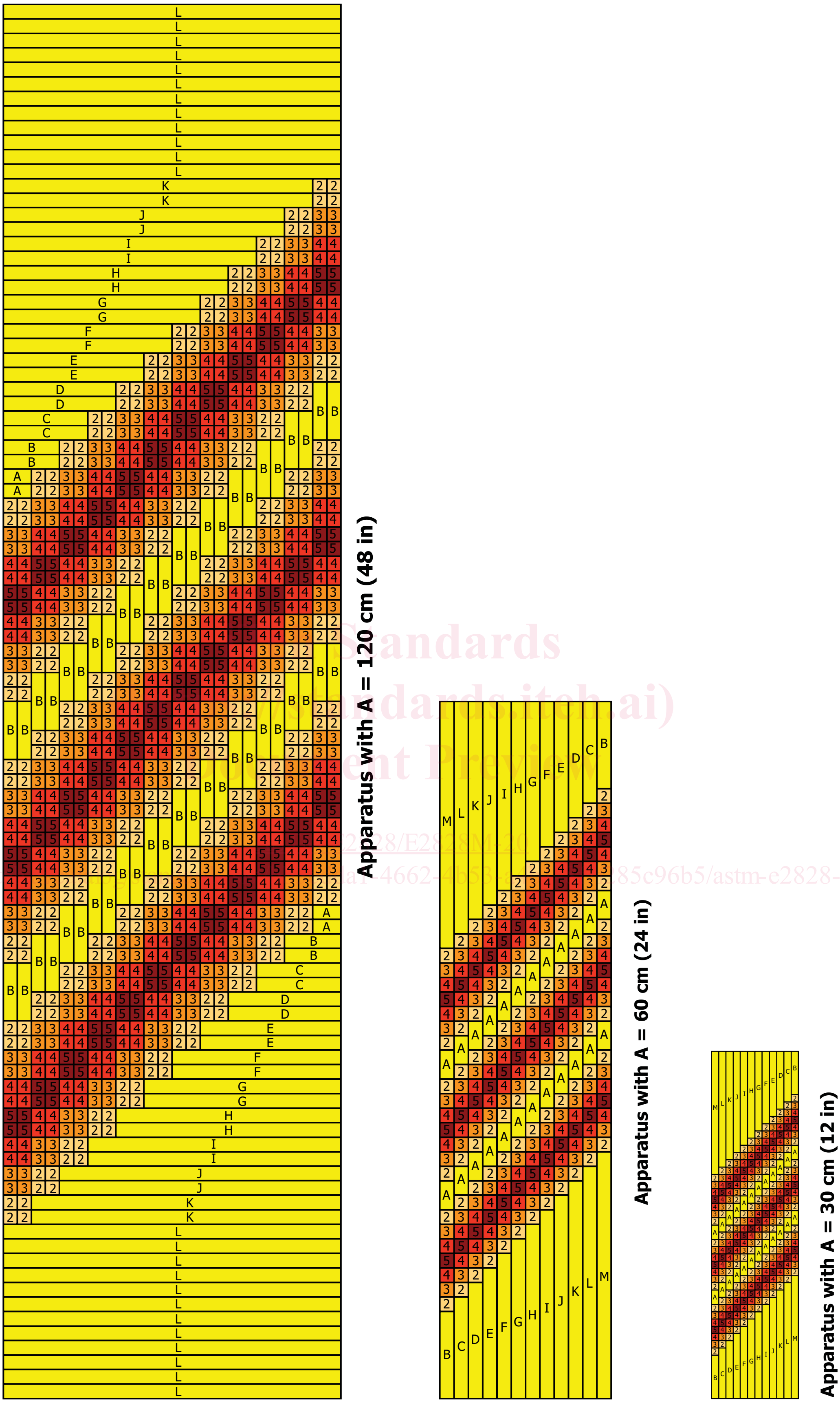


FIG. 7 Overview of Symmetric Stepfield