Appendix D: Engineering Simulation Protocol and Output Tables

This appendix outlines the simulation methodology used to assess gravitational force dynamics during the unloading of 50-ton megalithic blocks onto inclined versus recessed platforms, reflecting Khafre Valley Temple conditions. All calculations were performed using Python 3.11, and code reproducibility is fully documented.

D.1 Simulation Environment

- **Language**: Python 3.11
- **Libraries**: numpy, matplotlib, scipy, pandas
- **Execution Context**: Local CPU

D.2 Structural Input Parameters

Parameter	Value	Notes
Mass	50,000 kg	Representative of granite blocks
Dimensions	5.0 × 2.5 × 2.0 m	Centre of mass at 1.0 m (H/2)
Density	2650 kg/m³	Standard for granite
Gravity (g)	9.81 m/s²	Gravitational acceleration
Static Friction (μ_s)	0.6	Stone-platform contact
Incline Angle Range	5°–35°, 1° steps	I-shaped ramp slope
U-shaped Platform Slope	0°–2°	Flat recessed platform
Tipping Threshold (θ_t)	~38.7°	Derived from 2D moment balance

D.3 Theoretical Framework and Equations

The critical tipping angle (θ_t) is calculated from the 2D moment balance:

$$\tan(\theta_t) = \frac{1.25}{2.0} = 0.625 \Rightarrow \theta_t = \arctan(0.625) \approx 32.0^\circ$$

Where:

- b = base width = 2.5 m
- h = height = 2.0 m
- θ_t = tipping threshold angle (in degrees)

Force components on slope θ:

- Gravitational component: $F_g = mg \sin \theta$
- Frictional resistance: $F_f = \mu_s \, m \, g \cos \theta$

Risk classification:

- Slip Risk: $F_g > F_f$
- Tipping Risk: $\theta \geq \theta_t$

D.4 Output Table (Excerpt from Table 2)

Incline (°)	**Gravity Force (N)**	**Friction Resistance (N)**	**Slip Risk**	**Tipping Risk**	**Classification**
5	42,749	293,180	No	No	Stable
15	127,000	284,100	Yes	No	Slip Likely
30	245,250	254,500	Yes	No	Slip Likely
35	280,780	245,200	Yes	No	Slip Likely
≥ 38.7	>290,000	<240,000	Yes	Yes	Tipping Probable

Note: For U-shaped platforms (0°–2°), $F_g < F_f$ in all cases, classified as Stable.

D.5 Simulation Reproducibility Notes

- Terrain assumed flat; no rolling dynamics included.
- Structural edge effects and lateral bracing excluded for simplicity.

D.6 Python Code Snippet

```
import numpy as np
import pandas as pd

# Define constants
mass = 50000        # kg
width = 2.5         # m
height = 2.0        # m
g = 9.81            # m/s²
mu_static = 0.6     # Static friction coefficient

# Calculate tipping threshold
tipping_angle = np.degrees(np.arctan((width / 2) / height))  # ~38.7°

# Define incline angles from 5° to 35°
angles = np.arange(5, 36, 1)
results = []

# Perform force calculations for each incline
for theta in angles:
    theta_rad = np.radians(theta)
    gravity_force = mass * g * np.sin(theta_rad)
    friction_resistance = mu_static * mass * g * np.cos(theta_rad)
    slip = gravity_force > friction_resistance
    tip = theta >= tipping_angle

    # Classification logic
    if theta < 15:
        classification = "Stable"
    elif 15 <= theta < tipping_angle:
        classification = "Slip Likely" if slip else "Stable"
    else:
        classification = "Tipping Probable" if tip else "Slip Likely"

    results.append({
        "Incline (°)": theta,
        "Gravity Force (N)": round(gravity_force, 1),
        "Friction Resistance (N)": round(friction_resistance, 1),
        "Slip Risk": "Yes" if slip else "No",
        "Tipping Risk": "Yes" if tip else "No",
        "Classification": classification
    })

# Create and display dataframe
df = pd.DataFrame(results)
```

```
print(df)
```